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Design and performance assessment of chip seal applications

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Design and performance assessment of chip seal applications

by

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

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DEDICATION

Through my quest to pursue my PHD degree, I have always recited these verses in my heart, "For I can do everything through Christ, who gives me strength". (Philippians 4:13). I believe that the lord has accompanied me in every step I have taken, and in every success I have realized. In hardships, I had faith that Jesus will make me pass through everything peacefully, and this gave me confidence and persistence.

I want to dedicate this dissertation to my husband Kamal Abdel Shahid, who have always showed me all the love, support and encouragement. Thank you Kamal for being such an amazing role model as a husband, father and friend. You, Sophia and Adel are my ultimate source of joy and inspiration.

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NOMENCLATURE

A   Aggregate Absorption Factor

AADT   Annual Average Daily Traffic

ADT   Average Daily Traffic

ALD   Average Least Dimension

A_{ML} McLeod Aggregate Application Rate

A_{NZ} New Zealand Aggregate Application Rate

AR   Asphalt Rubber Binder

BWP   Between Wheel Path

D   Diameter of Sand Circle

DF   Degrees of freedom

DFT   Dynamic Friction Test

e   Surface Texture Correction Factor

F (P)   Failure Probability

FI   Flakiness Index

G   Bulk Specific Gravity

M	Median Size
MSE	Mean Square Error
MST	Mean Square Treatment
MTD	Mean Texture Depth
Mu	Coefficient of Friction
OWP	Outer Wheel Path
P	Surface Hardness Correction Factor
PBA	Performance Based Asphalts
PM	Preventative Maintenance Technique
PMB	Polymer Modified Binder
PME	Polymer Modified Emulsion
PUC	Performance Uniformity Coefficient
R^2	Proportion of Response Variability
R_{ML}	McLeod Binder Application Rate
R_{NZ}	New Zealand Binder Application rate
S	Surface Condition Correction Factor

S (P)	Survival Probability
SS	Sum of Squares
T	Traffic Factor
T_f	Adjustment Factor for Traffic
V	Voids in Loose Aggregate
W	Loose Unit Weight
Y_d	Design Lifetime

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ABSTRACT

The research evaluates the effectiveness of chip seal treatments when rational design, good materials, good construction and good agency oversight work together. The work investigates the effectiveness of chip seal applications using short-term and long-term quantitative test results from various chip seal roadways located in Oregon. Laboratory testing is utilized to understand and reflect the importance of aggregate characterization to ensure the success of performance. Findings show that chip seal preserved Oregon's roadways by improving their surface texture properties and protecting them from additional cracking and deterioration.

The study further evaluates the effect of various parameters on chip seal performance, such as: roadways' pre-seal condition, traffic volume, material properties and design quantities. In addition, statistical analysis using split plot repeated measures design is introduced to better understand the significance of factors, such as type of seal and environmental aging, on the performance. The study identified that chip seal performance is mostly affected by three factors, which are: underlying road condition, pre-seal texture condition and seal type. Statistical analysis of macrotexture results showed that seal type (hot applied versus emulsified) and environmental-aging of pavements along with their interaction effect are the most significant factors that affected the roadways performance.

Finally, the study develops localized performance and survival prediction models for chip seals using two-years of 14 Oregon projects' infield macro-texture data along with regression modelling. Findings reveal that chip seal treatments are estimated to extend the life of Oregon's asphalt pavements by an average of 10 years.

CHAPTER 1.   INTRODUCTION

1.1 Preventative Maintenance Techniques

In general, there are three broad categories of pavement project types: (1) preventative, (2) corrective, and (3) rehabilitation. Figure 1-1 shows the different stages of projects needed to sustain a pavement life and associated costs. Preventative and corrective actions are generally recognized as pavement maintenance techniques (PM) (Dessouky et al. 2011). PM is used to treat minor pavements' deterioration, and delay the need for rehabilitation and corrective maintenance. PM targets pavements with good to fair conditions to provide a more uniform performing system (Dessouky et al. 2011). Corrective maintenance is performed after a specific deficiency occurs in the pavement, and is usually applied as a routine treatment maintenance (e.g., pothole patching). When pavement preservation techniques are applied at the right time with good workmanship, substantial cost savings can be recognized compared to rehabilitating pavements, as shown in Figure 1-1.
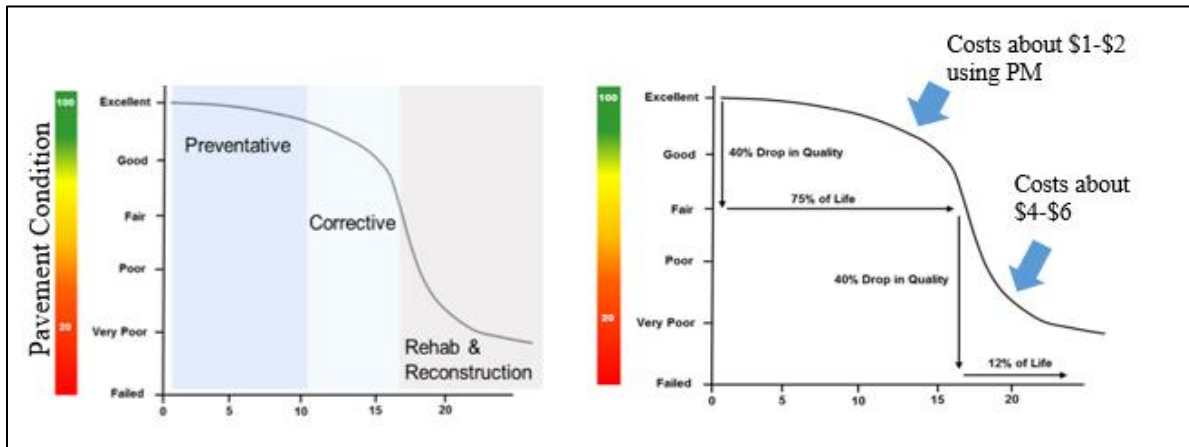
Figure 1-1 Pavement maintenance project types and costs (adopted from: Peshkin et al. 2004; Wilde et al. 2014)

PM programs strategically use preservation techniques to cost-effectively extend the life of pavements, and improve functional pavement characteristics (Wilde et al. 2014). There are a number of PM treatments for flexible pavements. Asphalt Institute and AEMA (2009) describes conditions for which each treatment would be the most effective. A summary of most common PM activities are (Galehouse et al. 2003): fog seals, chip seals, slurry seals, micro-surfacing, and thin hot mix overlay.

Many studies address the performance, expected service life and costs of each PM treatment. Table 1-1 shows different PM treatment techniques with their expected service life and costs, while Table 1-2 provides general guidance for selecting pavement preservation treatments based on distress types. Based upon performance and costs comparisons, chip seals can be considered a low-cost solution while addressing many pavement distresses.

Table 1-1 Estimated costs and life extension of pavement preservation treatments (Dessouky et al. 2011; Wilde et al. 2014)

Treatment	cost/yd^2	Expected life of treatment (years)		
		Min	Average	Max
Fog seals	0.45	2	3	4
Chip seals	0.85	3	6	12
Slurry seals	0.9	3	5	7
Micro-surfacing	1.25	4	7	24
Thin hot mix overlay	1.75	2	7	12

Table 1-2 Treatment types and corresponding distresses (Wilde et al. 2014)

Treat.	Fog seals	Chip seals	Slurry seals	Micro - surfacing	Thin hot mix overlay
Roughness				●	●
Rutting				●	●
Fatigue cracking	●	●	●	●	●
Longitudinal cracking		●	●	●	●
Transverse cracking		●	●	●	●
Bleeding		●		●	
Raveling	●	●	●	●	

1.2 Chip Seal Definition, Benefits and Types

Chip seal is a layered system of binder and aggregate chips working together to create desired surface properties. Figure 1-2 shows a cross section of a single chip seal application (Caltrans Division of Maintenance 2003). Chip seals effectively extend the pavement performance life in the following ways (Gransberg et al. 2010a; WSDOT 2015):

- Improves skid and texture properties,

- Prevents water paths into the roadway substrate,

- Seals cracks,

- Provides anti-glare surface,

- Increases reflective surface for night and wet driving,

- Reduces oxidation and aging effects, and

- Reduces roadways maintenance costs.

Chip seal design and construction practices have evolved since their origin in the 1930's through research studies and on-site performance monitoring (Patrick 2008; Patrick and Donbavand 1996; Pidwerbesky et al. 2006). Chip seal performance is greatly affected by

aggregates properties, type of asphalt binder and the relative amounts of each (Li et al. 2012; Visintine et al. 2015). Chip seal performance also relies on site factors such as weather, underlying roads conditions, traffic type/volume and aging.
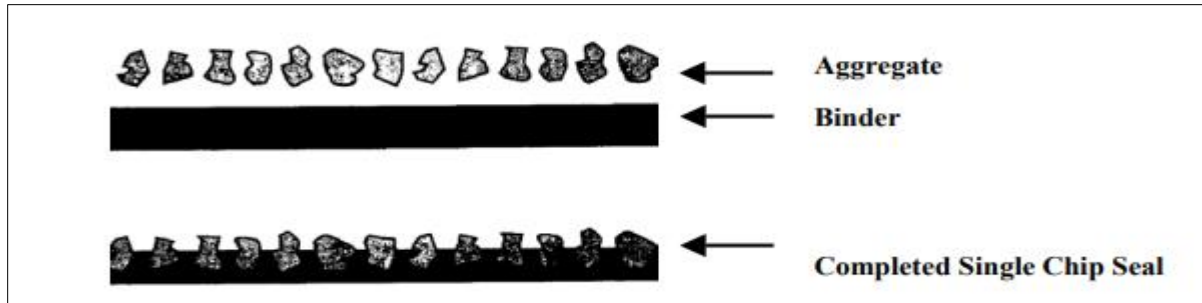
Figure 1-2 Cross section of a one-size seal coat aggregate (Caltrans Division of Maintenance 2003)

The layered chip seal system can be constructed using various techniques and materials. The most two commonly used chip seal types in the US are single and multiple chip seals (Caltrans Division of Maintenance 2003; Gransberg and James 2005). The list below discusses details for each chip seal type (Caltrans Division of Maintenance 2003; Gransberg and James 2005).

1. Single chip seal: This is the least expensive method. It provides a better skid-resistant wearing-surface and seals low to moderate severity cracks. This method is used for normal conditions that do not require any special treatment. The application method requires placing the binder first then placing the aggregates immediately. Rolling the aggregates to ensure desired embedment is a key issue.

2. Multiple chip seals: Consists of multiple layers of aggregate and binder. The application method is similar to single chip seals, except that an additional layer of binder and aggregate is applied over the first layer. The additional layer provides a more durable wearing surface. Additional rolling and sweeping are required between applications.

3. Racked in seal: A special type of surface treatment that requires the application of choke stones to fill the voids available in the seal. The choke stones help provide an impermeable seal as well as enhancing the bonding between the aggregates and the binder. This type of treatment is used in roads with large quantities of expected traffic wearing and turn arounds.

4. Cape seal: Includes a single chip seal application followed by a slurry seal. The slurry seal helps provide more shear resistance. It provides more strength and durability to the pavements. It is mostly used in residential and rural areas and in some cases in urban highways.

5. Inverted seal: Includes placing large aggregates on top of smaller aggregates to create an inverted seal. These seals are commonly used to correct existing surface irregularities through restoration of texture and uniformity to the surface.

6. Sandwich seal: Includes having one layer of binder application placed in-between two aggregates layers. Sandwich seals are used for absorbing excess binder on a flushed surface.

7. Geo-textile reinforced chip seal: Requires the use of geotextile products to enhance the performance of chip seal. This method is mainly used to restore surface problems, such as bleeding or cracking.

1.3 Chip Seal Design

Chip seals should be thought of as an engineered system based upon sound engineering principles (Gransberg et al. 2010a; Gransberg and James 2005). F.M. Hanson was the first researcher to present a scientific approach to chip seal design in the mid-nineteen thirties (Hanson 1934). His approach has provided the basis for most future design methods. Hanson provides a calculated estimate of the application rates of the asphalt and aggregate chips

based on a specific embedment depth. Hanson's approach is based on the concept that the amount of binder required to embed the aggregates is directly related to the volume of voids in the chip seal. Hanson specified the percentage of the voids to be filled by residual binder to be between 60-75 percent (Gransberg et al. 2005). Figure 1-3 shows the effect of voids on the design. The evolution of roadway infrastructure needs has required further refinement to chip seal designs to better understand the effect of field conditions on the required application.
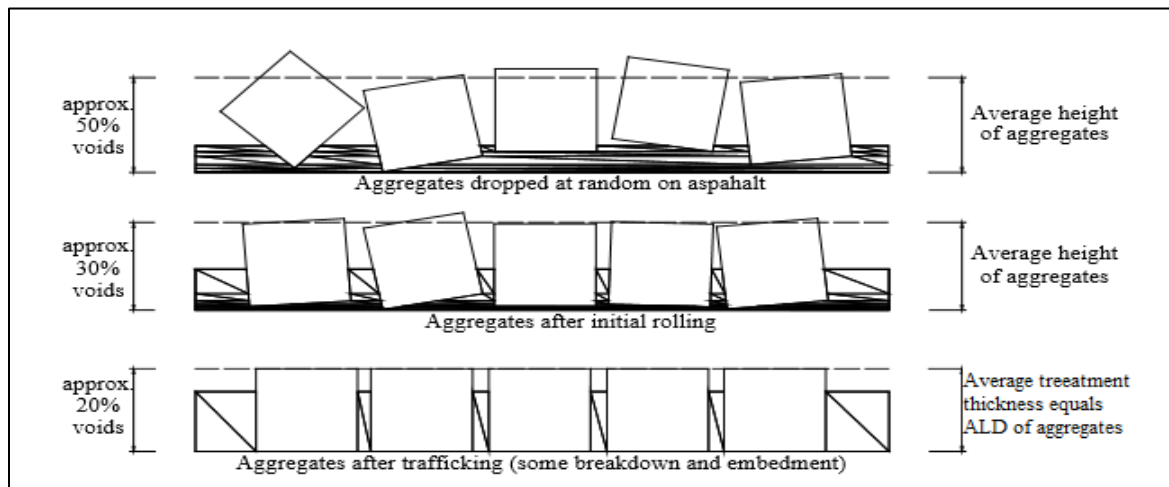
Figure 1-3 Aggregate embedment illustration (Kim and Adams 2011)

1.4 Chip Seal Construction

Figure 1-4 shows the sequence of chip seal construction. After surface preparation, the chip seal distributer applies the asphalt binder as shown in Figure 1-4(a). Figure 1-4(b) shows the spray fans of the spreader, when the binder is applied. Figure 1-4(C) shows the Chip spreader, and Figure 1-4 (d) shows the pneumatic roller, which embeds the aggregates to the binder.

Figure 1-4 Chip seal construction sequence (Photo credit Paul Ledtje)

1.5 Problems Statement

The main obstacles to achieving successful chip seal roadways are practitioners' reliance on experience and empirical methods rather than an engineered framework. In addition, only limited studies in the US have focused on investigating the relationship between chip seal design, laboratory testing and chip seal field performance. Consequently, various agencies throughout the state have reported that they were not obtaining a consistent quality of performance. As agencies struggle to fund cost effective preservation programs, studies which document the high cost-benefit of chip seals provides agencies with a strategic value. In addition, more numerical studies that address chip seal design and performance-monitoring practices would constitute a great value to the industry and research.

1.6 Organization of Dissertation

In this research, chip seal design and performance evaluation are conducted using laboratory testing, field-testing, and performance monitoring. The research further integrates design and performance data into a management platform that can provide chip seal design rates checks, life cycle costs estimation, performance prediction and survival probabilities. The research consists of nine chapters as follows:

Chapter 2 presents a study to understand the effect of using chip seals as a preservation strategies on the performance of various Oregon State flexible pavements. The study conducts aggregate evaluation testing and pavement evaluation based upon surface texture properties and distress appearances. Chapter 3 provides a more comprehensive analysis of parameters affecting chip seal performance such as material types and properties, traffic volume and pavements pre-seal condition.

Chapter 4 documents a statistical analysis using split-plot repeated measures (SPRM) to investigate the effect of seal type and aging on chip seal macrotexture properties. The study uses infield sand circle test results of two years monitoring period to conduct the repeated measures analysis.

Chapter 5 demonstrates the importance of using rational chip seal design approaches to ensure performance success. The study compares between Oregon-based chip seal projects actual application rates, and back-estimated rational design quantities using McLeod and New Zealand methods. The study correlates between selected project's application rates and their field performance, focusing on embedment parameters and estimated service life.

Chapter 6 provides a localized prediction model for chip seal pavements performance. The study is built upon previous research that promotes the use of localized chip seal pavements' macrotexture properties to develop performance deterioration models. In

addition, based upon localized chip seal field performance, a survival study is presented to indicate the probability of survival of chip seal projects at a given treatment age. The proposed platform is intended to feed other planning and/or scheduling platforms such as life cycle cost analysis models, or agencies' planning and budget allocation models. Finally, chapter 7 presents major conclusions of the research study as well as suggestions for future research.

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CHAPTER 2.   PERFORMANCE EVALUATION OF EMULSION AND HOT ASPHALT CEMENT CHIP SEAL PAVEMENTS IN OREGON

Modified from a paper published in Journal of Materials in Civil Engineering

Minas Guirguis[a]* and Ashley Buss[a]

Abstract

Pavements steadily deteriorate due to many factors such as weather, traffic, water infiltration, and degradation of materials over time. Environmental and mechanical weathering, such as traffic loading, exposure to sun, water, freezing and thawing lead to pavement deterioration and ultimate failure, if maintenance and preservation is not performed at the right time. The main objective of this study is to verify the performance and effectiveness of using chip seal preservation techniques in Oregon.

Two testing schemes are used, the first includes aggregate testing with an attempt to investigate how aggregate performance could relate to chip seal performance. The aggregate testing that would later reflect the pavement performance, and included; gradation, flakiness, abrasion resistance, and embedment.

The second testing scheme includes chip seal case studies' pavement evaluation using field-testing. Chip seal evaluation emphasized pavement micro- and macro-texture properties using measurements of mean texture depth and friction parameters. Moreover, pavement assessment includes evaluating the pavement performance based upon distress appearances.

Findings show that aggregate properties have a significant contribution to the overall performance of chip seal pavements. Results further show that chip seals provide a significant performance improvement in pavement test sections by reducing the appearance of distresses after two-years of service life. The study concludes that chip seal is an effective

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preservation tool when constructed with good quality aggregates and binders based on the documented improvement in cracking for all test sections observed.

2.1 Introduction

2.1.1 Background

United States roads and highways are an immense public investment, and are considered vital for people and vehicle use on daily basis. According to the National Center for pavement preservation, "There are nearly 4 million miles of paved public roads in the United States, valued at $1.75 trillion"(O'Doherty 2017). Highway agencies are interested in preserving this investment by studying and understanding pavement preservation effectiveness through research, implementation of best practices and outreach. One cost-effective preservation technique worth investigation is chip seal, where a layered system of binder and aggregate chips works together to create desired surface properties.

McLeod chip seal design specifies the use of uniformly graded aggregate gradations for improved performance and introduces a uniformity index. Lee and Kim (2009) improved this concept with the performance uniformity coefficient (PUC) which quantifies the allowable tolerance for particle sizes for bleeding and aggregate loss. Equation (2-1) shows the calculations for PUC (Zaman et al. 2014)

$$PUC = P_{EM} / P_{2EM}$$ Equation 2-1

Where P_{EM} is indicative of bleeding potential and equals percent passing at a given embedment depth, and P_{2EM} is indicative of aggregate loss and equals percent passing at twice the given embedment depth. According to Lee and Kim, as the PUC approaches zero, the aggregate gradation becomes increasingly uniform. Uniform gradations are important for chip seal performance and ensuring each aggregate is contributing to the overall chip seal

system. The smallest aggregates and/or fines contribute to bleeding and conversely, oversized aggregates contribute to aggregate loss during construction, brooming and subsequent traffic use (Lee and Kim 2009).

2.1.2 Design

Chip seals are key components to any pavement preservation program (Galehouse et al. 2003). (Hanson 1934) and (Kearby 1953) developed strategies for chip seal design more than 60 years ago, yet McLeod method is the most widely adopted approach to chip seal design. (Epps et al. 1981) proposed further modifications to the design method in the early 1980's. Australia, Canada, New Zealand, South Africa, United Kingdom, and the United States have also conducted in-depth studies to further develop chip seal design methods (Beatty, T. L. 2012; Broughton et al. 2012; Gransberg and James 2005).

Chip seal design methods provide a framework for agencies to implement best practices, design techniques and improve specifications. The pavement macrotexture, hardness of the surface, initial pavement condition and structural capacity can play an important role in the design process, and the determination of binder application rates. Material evaluation and selection should also consider the best type of binder for the job, traffic and the budget constraints. Aggregate gradation, uniformity, angularity, resistance to degradation and absorption also play significant roles in the performance of chip seals. Traffic can play a key role in the success of a surface treatment, and special design considerations are necessary with high average daily traffic (ADT).

In general, chip seal design procedures are based on volumetric characteristics of the sealing aggregate and binder. The design method provides a working estimate for determining the quantity of binder required to hold the aggregate gradation in place

(Gundersen et al. 2008). Chip seal design methodologies generally assume that aggregates are placed in a single-stone layer.

Other considerations in the design application rates include terrain, pavement geometry, volume of voids in the seal and the traffic level (Zaman et al. 2014). Trafficking will affect aggregate embedment into the binder. Adjustment factors are used in the chip seal design formula to increases or decrease the binder application rate as required. The true design rate may also vary along the length of the road and depends upon the size, shape and orientation of the aggregate particles, embedment of aggregate into the underlying pavement, texture of the surface, and absorption of binder into either the pavement or aggregates (Kim and Adams 2011).

2.1.3 Materials

Chip seals can be constructed using hot-applied or emulsified asphalt binders. The hot-applied asphalt is often polymer modified and similar to what is used in hot mix asphalt. Asphalt emulsions contain approximately 31 percent water and 68 percent asphalt bitumen as well as a small percentage of emulsifiers. The emulsified asphalts contain asphalt globules dispersed in water and stabilized with an emulsifying agent. The oil-in-water emulsion undergoes a manufacturing process through a colloidal mill that allows the binder to be applied at lower temperatures than the hot-applied asphalt.

Asphalt emulsions are graded based on the electric charge surrounding the asphalt particles: anionic, cationic and non-ionic. Typically, cationic emulsions are used in chip seals. Emulsions are further categorized upon how quickly they "break" or "set"; asphalt emulsions are classified as rapid set, medium set, slow set and quick set (Asphalt Institute and AEMA 2009). There are also high float emulsions that have a gel structure, and resist flow of the emulsion residue. For chip seals, rapid set and medium set emulsions are used,

but rapid-set is the most common. The rate at which the emulsion breaks will depend on the emulsion chemistry, ambient temperature, moisture content and absorption properties of the aggregate, wind speed and the traffic/compaction loading. One of the most critical factors is humidity. One commonly referenced manual (Read and Whiteoak 2003) recommends that at 80 percent humidity and above, the emulsion should only be applied on minor roads, where the traffic can be slowed to 10-20 mph.

2.1.4 Objectives and scope

The objective of this research is to attempt to understand the effect of using chip seals preservation strategies on the performance of pavements. Two testing schemes are specified in this study to cover both aggregate performance and chip seal performance. Testing schemes are further applied to case studies including eight chip seal pavement test sections in the State of Oregon. Attempts to correlate between both performances are made to show how aggregate properties can significantly affect the overall performance of chip seal.

Aggregate evaluation testing includes gradation, flakiness and abrasion resistance; while pavement evaluation testing includes major emphasis on pavements' micro and macro texture properties with measurements of mean texture depth and friction parameters.

Pavement evaluation assessment includes evaluation of pavement's performance based upon distress appearances. Distresses evaluated are transverse, longitudinal, fatigue, pothole, patching, bleeding, loss of aggregate, rutting and raveling. Pavement condition was analyzed prior to construction, right after construction and up to two-year post construction.

2.2 Oregon Chip Seal Pavement Project Overview

In this research, chip seal projects near Klamath Falls, Oregon were selected for study. During the 2014 construction season, the Klamath Falls project had multiple chip seal sections constructed within close proximity and the seal treatments used both emulsified asphalt and hot-applied asphalt during application.

Table 2-1 provides information about each chip seal section including location, estimated traffic flow (Annual Average Daily Traffic AADT), initial road condition and the type of binder material used in construction.

Four hot-applied chip seals and four emulsified chip seals test sections were constructed and monitored as part of this study. Other important factors include the pavement quality beneath the chip seal, identified as the pre-seal condition. Table 2-1 provides a general estimate of the road condition based on Oregon DOT pavement condition data. It is apparent that pavement condition varied from good to poor. Unit B had the worst underneath pavement condition, and Unit D has the best initial pavement condition. The underlying pavement condition is important when comparing between chip seal performance and will be further discussed when analyzing the results.

Another important consideration is the climate and weather conditions. Chip sealing construction conditions highly favor dry weather. According to the United States Department of Agriculture, Oregon's climate is generally cold in winter and mild in summer ranging from 30 to -25 °C, with frequent rain throughout the year. In certain regions of the State, specifically the Northwestern region of Oregon, large amounts of rainfall reduce the chip sealing construction season. Oregon Department of Transportation construction specifications limit chip seal construction season to July and August for climatic reasons.

Table 2-1 Oregon projects identification

Test Section Name	Location: Klamath Falls Roads	Seal Type	Est. AADT	Binder Detail	Pre-seal Road Condition
Klamath Unit A	OR - 62	Single Application Emulsified Asphalt Surface Treatment	460	CRS-2P	Fairs
Klamath Unit B	OR - 140	Aggregate Asphalt Surface Treatment	2300	AC-15P	Poor
Klamath Unit C	OR - 66	Aggregate Asphalt Surface Treatment	2900	AC-15P	Poor
Klamath Unit D	Trigley Ln./Miller Isle Rd.	Aggregate Asphalt Surface Treatment	1280	AC-15P	Good
Klamath Unit E	OR - 140	Aggregate Asphalt Surface Treatment	1345	AC-15P	Fair
Klamath Unit F	Hwy 50	Single Application Emulsified Asphalt Surface Treatment	2650	CRS-2P	Fair
Klamath Unit G	OR - 70	Single Application Emulsified Asphalt Surface Treatment	670	CRS-2P	Fair
Klamath Unit H	OR - 31	Single Application Emulsified Asphalt Surface Treatment	690	CRS-2P	Fair

Table 2-2 shows infield approximate application rates, and aggregates' sources for each test section. Aggregates used in Klamath Units (B, C, D and E) were the same crushed stone granite aggregates.

Table 2-2 Field application rates

Test Section	Binder Application Rate (l/m^2)	Chip Application Rate	Aggregate Origin (Quarry)
Klamath Unit A	2.17	0.012 m^3/m^2	Lyon Pit (gravel)
Klamath Unit B	1.68	9.76-10.85 Kg/m^2	Farmers S & G (crushed stone)
Klamath Unit C	1.68	9.76-10.85 Kg/m^2	Farmers S & G (crushed stone)
Klamath Unit D	1.68	10.85 Kg/m^2	Farmers S & G (crushed stone)
Klamath Unit E	1.63	10.31 Kg/m^2	Farmers S & G (crushed stone)
Klamath Unit F	2.27	0.012 m^3/m^2	Farmers S & G (crushed stone)
Klamath Unit G	2.27	0.012 m^3/m^2	Farmers S & G (crushed stone)
Klamath Unit H	2.36	12.48 Kg/m^2	Picture Rock Pit (gravel)

2.3 Analysis of Results

2.3.1 Aggregate performance properties

Aggregate laboratory testing is conducted to assess the quality of aggregates used in construction, and study its effect on the pavement overall performance. General aggregate properties such as specific gravity, density and percent absorption are measured to understand the nature and properties of used aggregates. Table 2-3 shows different test sections' aggregates and their specific gravities, densities and percentage absorption. Test results show the chip seal aggregates used in all test sections are of good quality.

Sieve analysis was performed for the aggregates used in the eight test sections, and aggregate gradations are shown in Figure 2-1. An ideal gradation for chip seal is a uniform gradation. All aggregates were found to be uniformly graded.

Table 2-3 General aggregate properties

Test Section	Specific Gravity (SSD)	Apparent Specific Gravity	Density (SSD) (kg/m³)	Absorption %
Unit A Klamath Chips	2.667	2.760	2661	2.01
Units (B- E) Klamath Chips	2.672	2.67	2595	1.63
Units (F & G) Klamath Chips	2.638	2.730	2632	2.06
Unit H Klamath Chips	2.579	2.691	2573	2.65
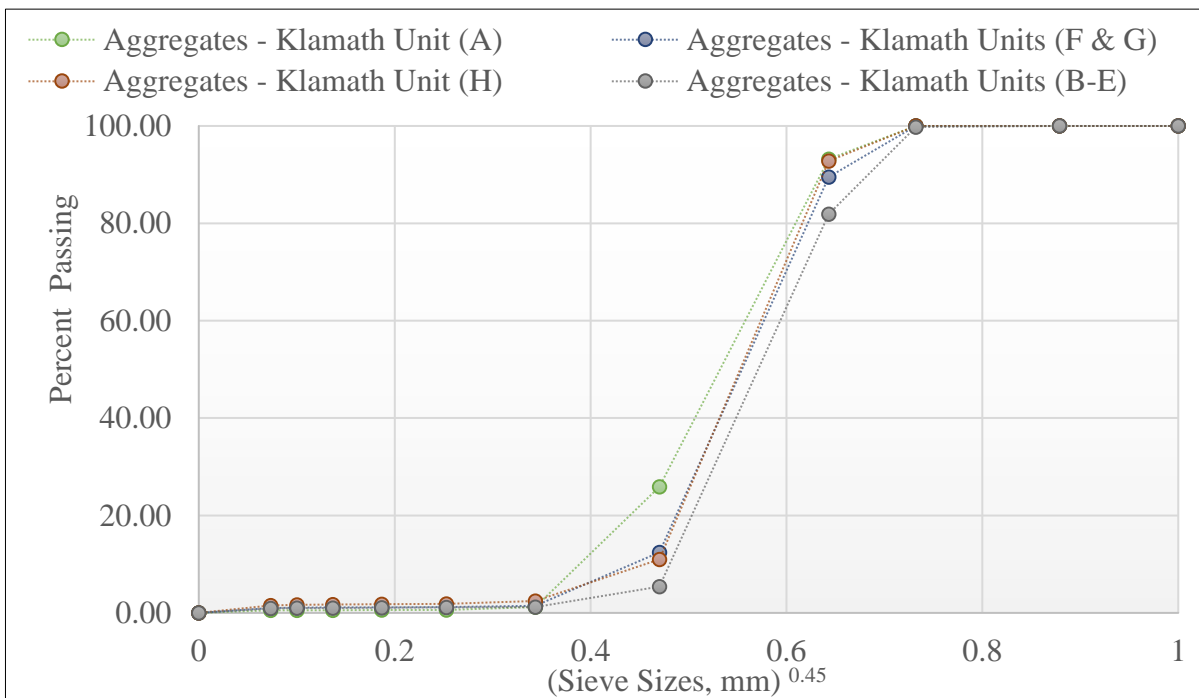
Figure 2-1 Power chart for aggregate gradations

PUC is a gradation-based performance indicator that represents the degree of uniformity of chip gradation using the concepts of McLeod's failure criteria. The smaller the PUC value, the more uniform the aggregate gradation would be (Lee and Kim 2009). The performance uniformity coefficient (PUC) and aggregates contributing to bleeding and loss were calculated, and shown in Table 2-4. Results show that Unit H had the most-uniform gradation, while Unit A had the least aggregates' uniformity properties. Overall, all aggregates acquired satisfactory performance regarding their uniformity.

Findings further show an acceptable percentage of flat particles compared to the standards recommendation of 25 percent (Shuler et al. 2011). Micro-Deval abrasion testing was further performed to assess the abrasion resistance of the chip seal aggregates. Results indicate that tested chips passed the requirements for abrasion resistance, with equivalent performance of percentage loss of 6 to 7 percent, which satisfies the standards recommended limit of 40 percent (Shuler et al. 2011).

Table 2-4 Aggregates' performance Properties

Test Section Chips	Aggregate contributing to bleeding (P_{EM}), %	Aggregate contributing to loss ($100-P_{2EM}$), %	Performance Uniformity Coefficient (PUC)	Flakiness Index (FI)	Micro-Deval abrasion %
Unit A Klamath	33	20	0.41	13.1	6.09
(Unit B-E) Hot Applied Klamath	16	18	0.20	5.2	7.21
Unit F &G Klamath	11	10	0.12	6.4	7.45
Unit H Klamath	11	6	0.12	12.1	8.6

2.3.2 Pavement texture performance

Sand circle test (Mean texture depth - MTD)

Pavements' microtexture is a function of the frictional properties of the aggregate used itself, while macrotexture is a function of the aggregate size, shape, and gradation. Macrotexture can be used as an indicator of aggregate loss, and can be assessed by measuring the mean texture depth (MTD) using New Zealand sand circle test procedure.

Sand circle test is a volumetric test, performed by placing a known volume (45 ml) of sand on the pavement surface. A disc is used to spread the sand until it is levelled with the top of the surface aggregate (Transit New Zealand 2002). The diameter of the formed sand circle is measured in two directions, and the average diameter of the circle is used in Equation 2-2. The surface texture is inversely proportional to the diameter of the circle on the surface of the pavement.

$$MTD = 57,300 / Diameter^2 \qquad \text{Equation 2-2}$$

Where, MTD = mean texture depth, mm

Diameter = average diameter, mm

In this study, sand circle test was conducted before and right after construction in all studied test sections. Follow up measurements were taken at one-year and two-years post construction, and results were compared to New Zealand performance specification, which define a minimum MTD failure criterion of 0.9 mm. MTD measurements were taken between the wheel path (BWP), and in the wheel path closest to the outside of the roadway (OWP). Figures 2- 2 to Figures 2-9 show the MTD performance of Units A to H over the two-year monitoring period, BWP and OWP.

All units had initial improvement after chip seal application, which then decreased over the first and second years due to traffic and environmental exposures. Based upon New Zealand specifications, all units appear to be performing well. Figure 2-3, Figure 2-4 and Figure 2-7 shows that Unit B, Unit C and Unit F have failed New Zealand minimum criteria of 0.9 mm at their pre-seal condition. Units B and C had the poorest underlying roads condition, which most probably have affected the roadway surface texture. Unit F had fair underlying conditions, yet acquired the highest longitudinal and transverse cracking distresses along its roadways. This would be discussed later in details, and might have been the reason of the poor texture performance before chip seal application.
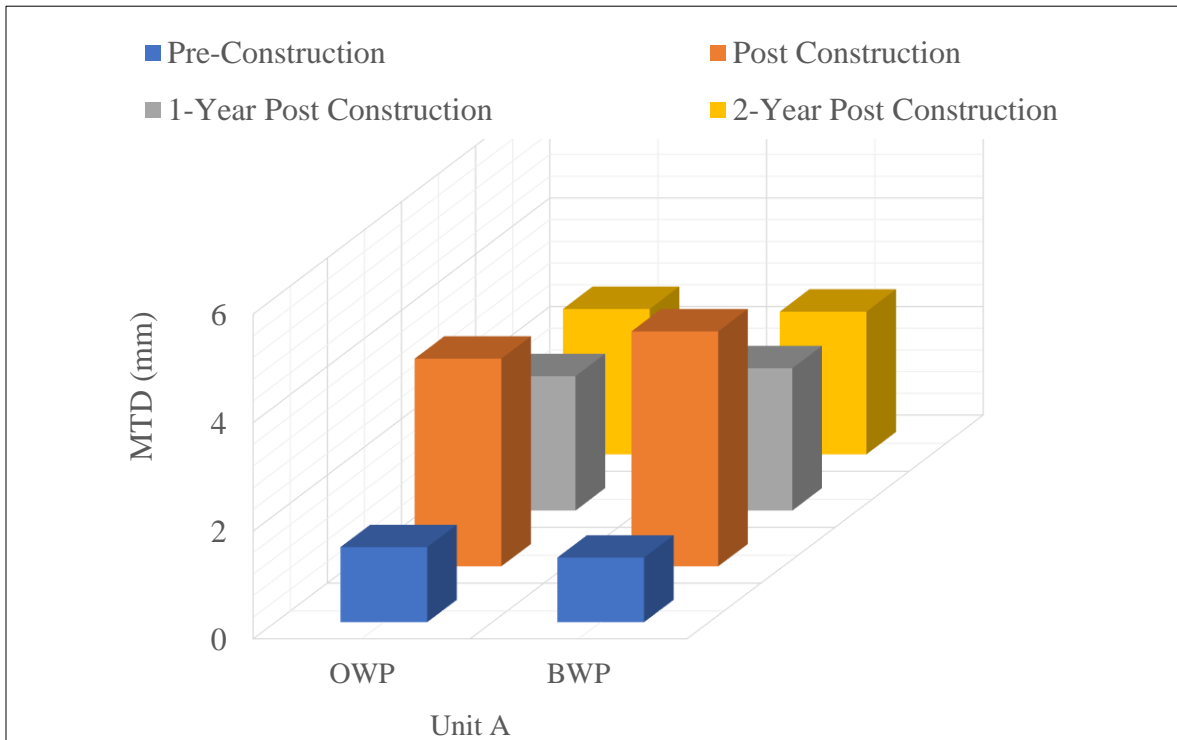
Figure 2-2 MTD results (Unit A)
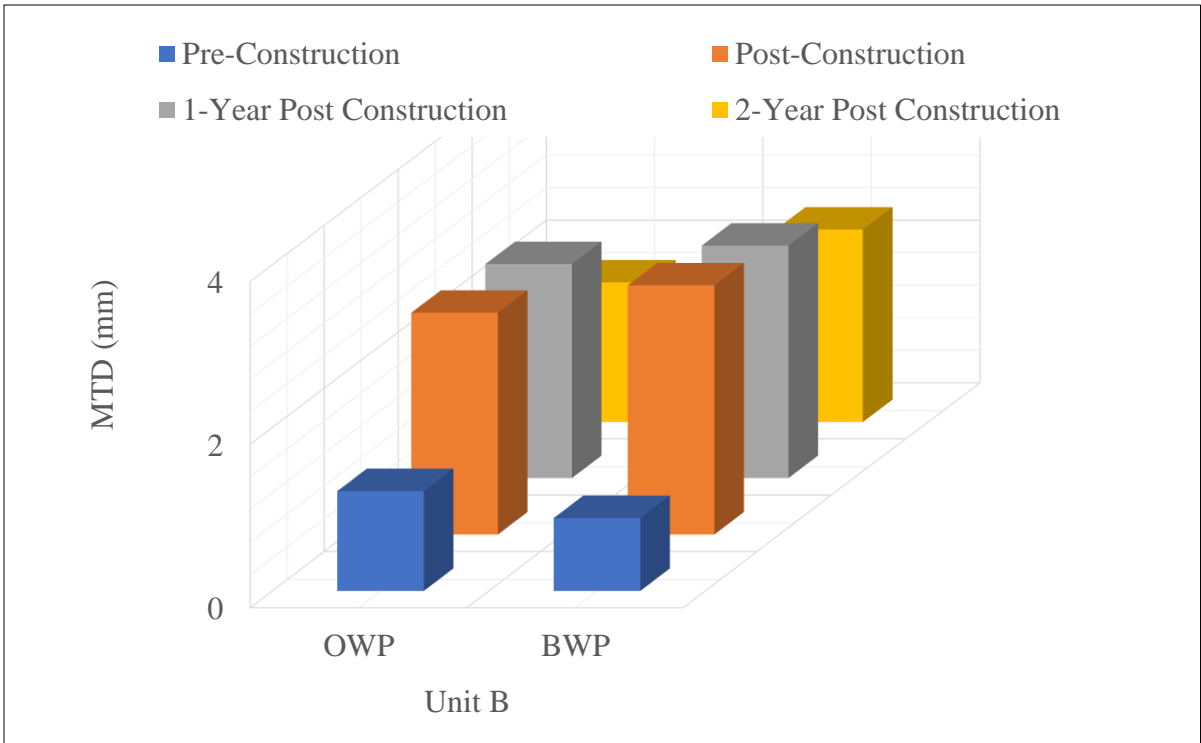
Figure 2-3 MTD results (Unit B)
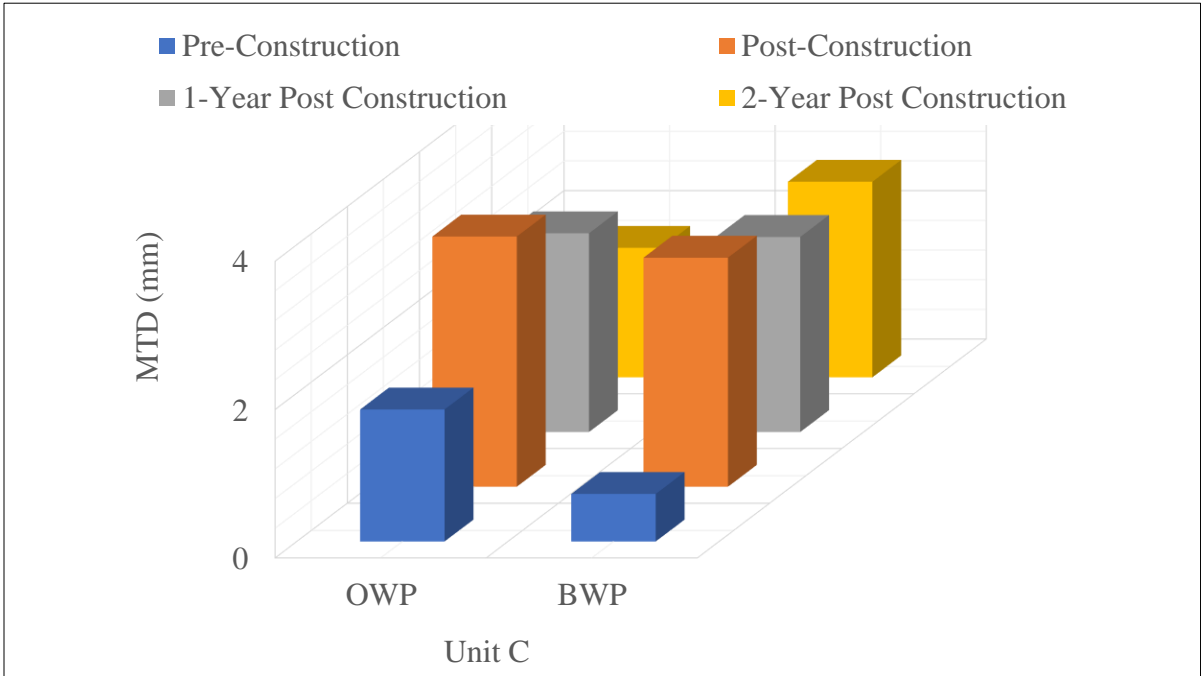
Figure 2-4 MTD results (Unit C)

The rate of MTD loss from one year to two years' post construction was recorded for all units, and reported the highest for Unit E. In general, hot-applied asphalt units (B, C, D and E) had a lower initial MTD when compared to emulsified asphalt Units (A, F, G and H). This expected due to the nature of the binder used. Despite that, emulsified based Units (A, F, G and H) have lost their texture depth at a faster initial rate than hot applied based Units (B, C, D and E). Emulsified Units' (A, F, G and H) MTD decreased highly during the first year; however, the rate of decrease leveled off between one and two years' post construction.

In general, all chip seal sections performed well compared to New Zealand chip seal performance specifications even units B, C and F that initially had poor road condition. Some correlations between underlying road conditions and distresses occurance were observed on the MTD response of studied roadways. Observed distresses correlation to performance would be discussed later in more details.
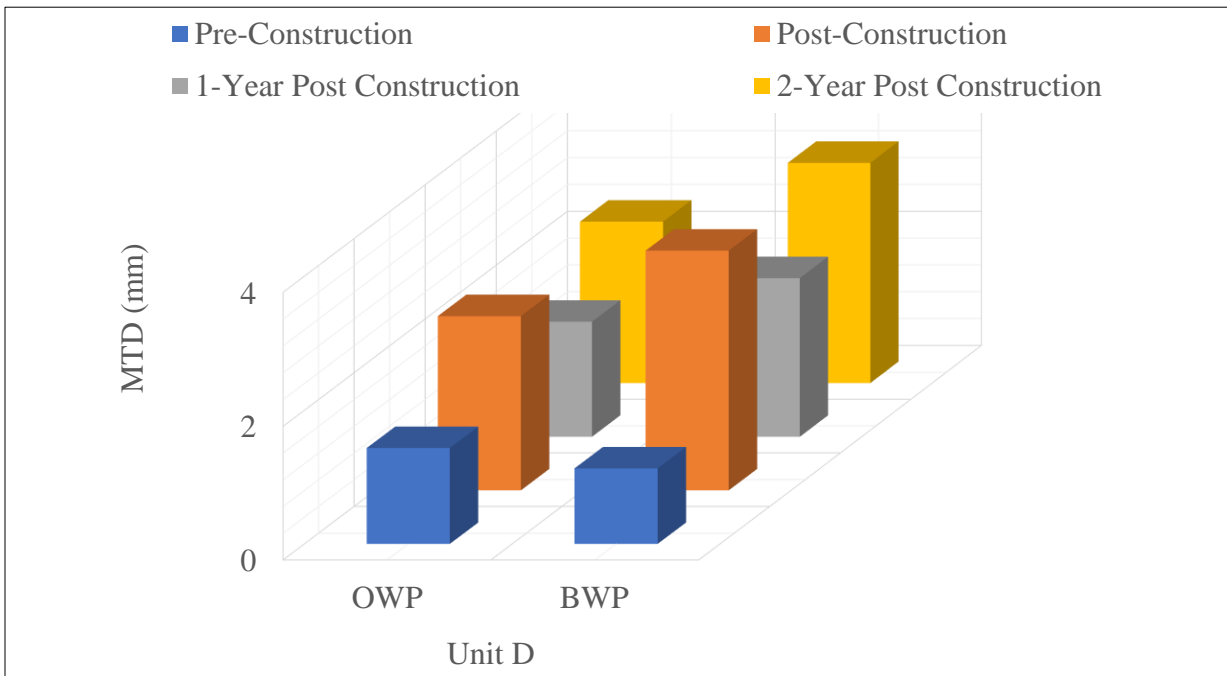
Figure 2-5 MTD results (Unit D)
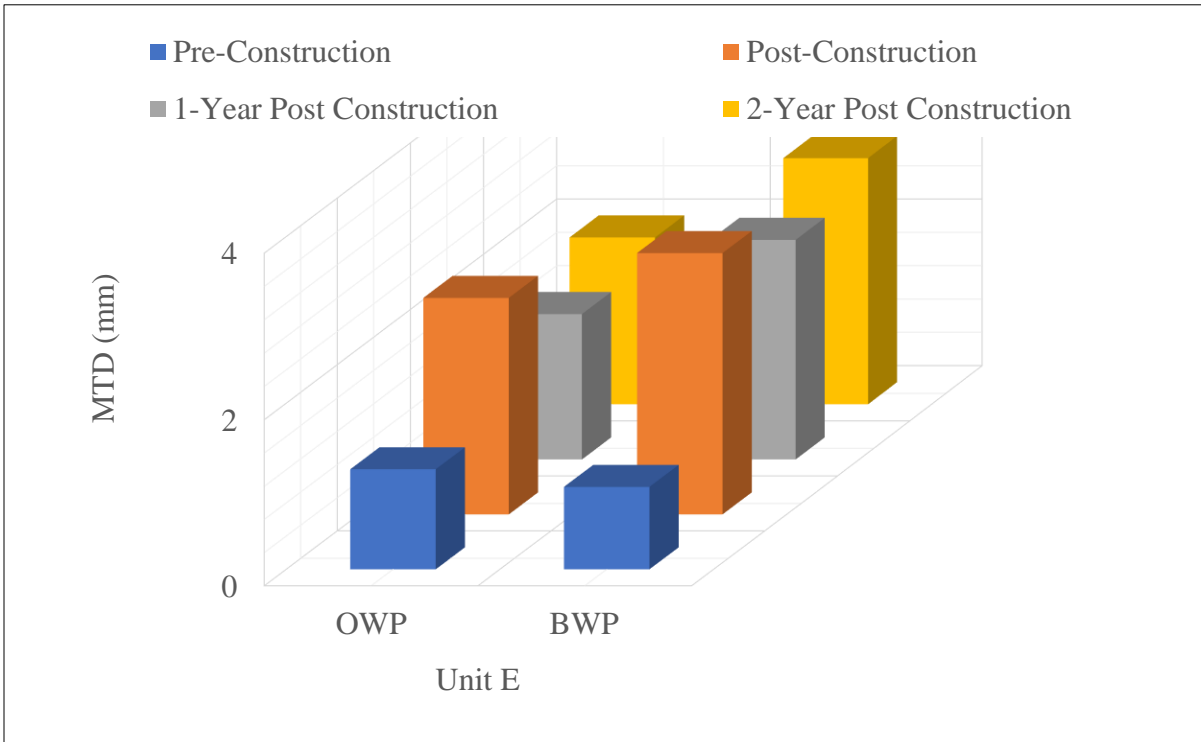
Figure 2-6 MTD results (Unit E)
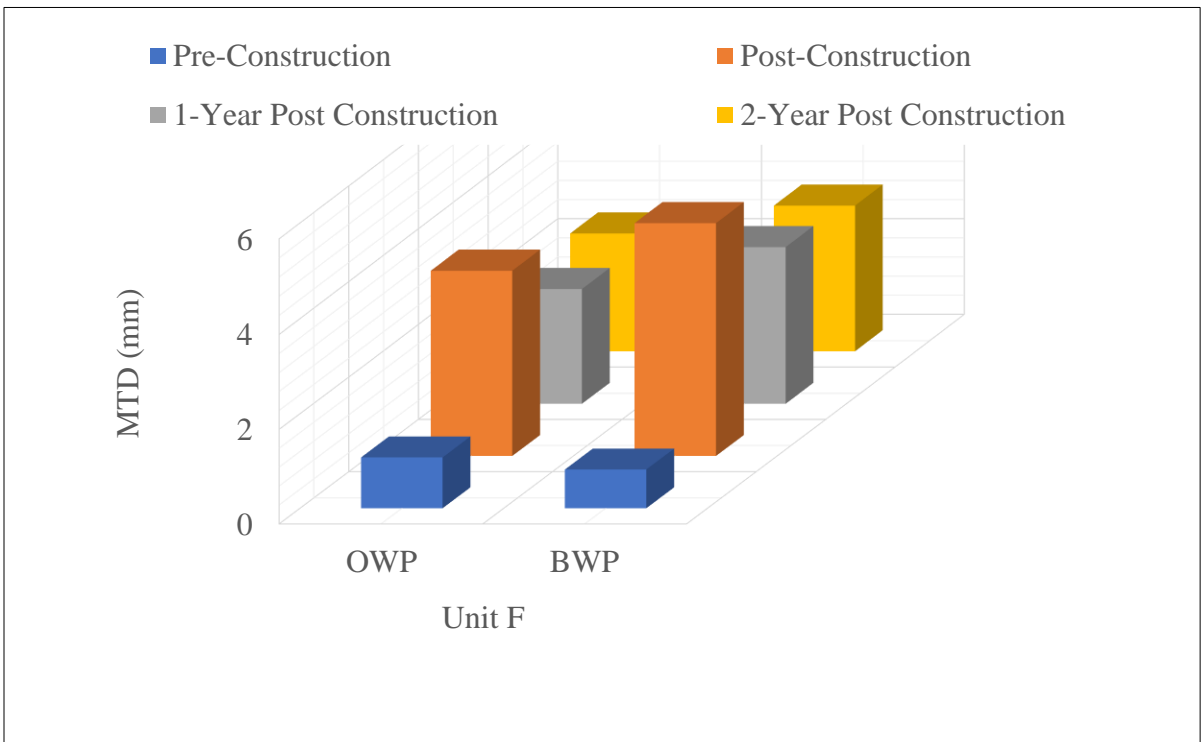
Figure 2-7 MTD results (Unit F)
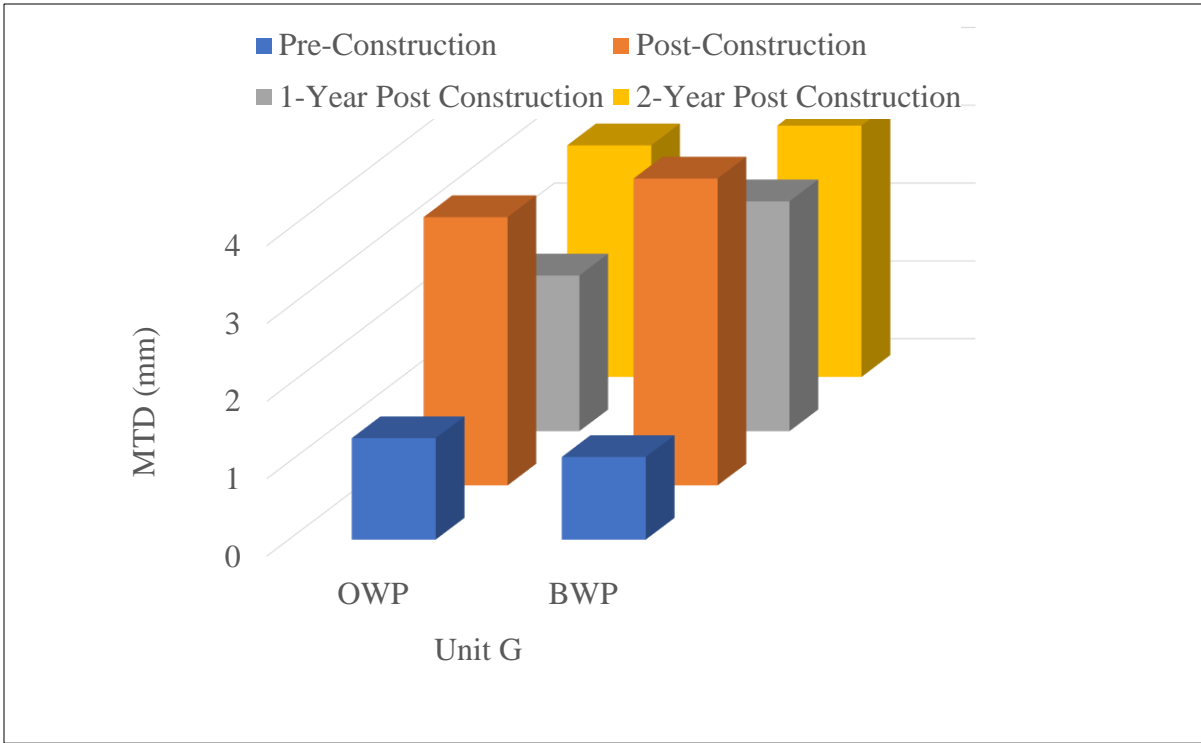
Figure 2-8 MTD results (Unit G)
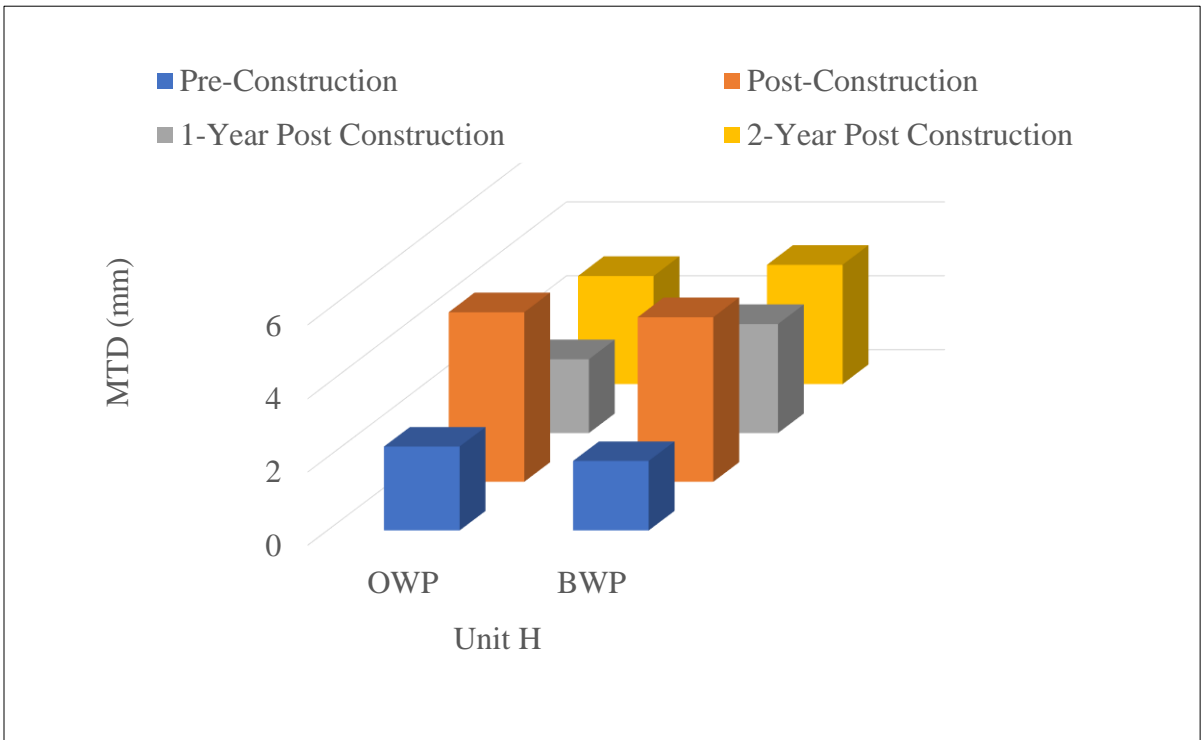
Figure 2-9 MTD results (Unit H)

Aggregate embedment is one of the most important properties for chips seal performance. McLeod and New Zealand chip seal design methods determine their application rates based on the concept of aggregate embedment. An appropriate amount of embedment will reduce aggregate loss, but too much embedment will lead to flushing and/or texture problems (Gransberg et al. 2005).

Design methods specify that aggregate embedment into binder should be in the range 70 percent after trafficking (Hanson 1934; Kearby 1953; McLeod et al. 1969). Yet, aggregate embedment tends to increase with time, as chips are rolled and trafficked. During rolling, the particles are reoriented to their least dimension and embedded to the binder (Gransberg and James 2005). The embedment depth can be expressed as a function of the ALD and the measured MTD, which follows the relationship in Equations 2-3 (Shuler 2011).

According to NCHRP Synthesis 342 Chip Seal Best Practices, the average least dimension (ALD) is "a metric that represents the expected chip seal thickness when the aggregate is oriented to lie on its flattest side". The ALD is often used as a design parameter that can be measured directly or estimated from the median size and flakiness index as follows in Equation 2-4.

$$E = \frac{ALD - MTD}{ALD}$$
<div align="right">Equation 2-3</div>

$$ALD \ (mm) = [M.S / 1.139285 + (0.011506) * FI]$$
<div align="right">Equation 2-4</div>

Where, ALD = Average least dimension, mm

MS = Median size, mm

FI = Flakiness index, percent

Final embedment depth is preferred to be in the range of 60 to 80 percent. Having an embedment lower than 60 percent leads to major bonding problems, and higher than 80

percent leads to a reduction in macrotexture properties, which causes friction-related safety concerns (Aktaş et al. 2013). Figure 2-10 displays the percent embedment estimate using Equation 2-3 for all test sections measured at post-construction, 1-year post construction and 2-years post construction.

A paper by (Shuler and Lord 2010) shows that estimating embedment using Equation 2-3 is going to provide an underestimate compared to actual measured chip embedment. For initial post-construction embedment, the values are underestimated due to the presence of excess chips still on the roadway surface, which leads to higher texture depths. In addition, there is a challenge with calculating the percent embedment with this method; as ALD is a laboratory-measured parameter, while MTD is a field-measured parameter. After construction, it is likely that not all aggregates are positioned on their ALD. However, the calculated percent embedment does provide a comparison between sections embedment properties.

Units A, F and H, which are chip seals constructed with emulsified asphalt, have a relative low initial embedment, which highly increased over the two years of trafficking. Emulsified asphalt units embedment estimate did not reach 50 percent. Units B, C and E, which are hot-applied asphalt chip seals, have shown acceptable values of embedment depth, which also increased after two-years of service life. Units D and G showed increased embedment at the first year, but a higher loss of embedment was observed in the second year. This may be related to their aggregate texture loss observed in their MTD results. In general, emulsified asphalt Units (A, F, G and H) have lost their texture depth at a faster initial rate than hot applied asphalt Units (B, C, D and E).
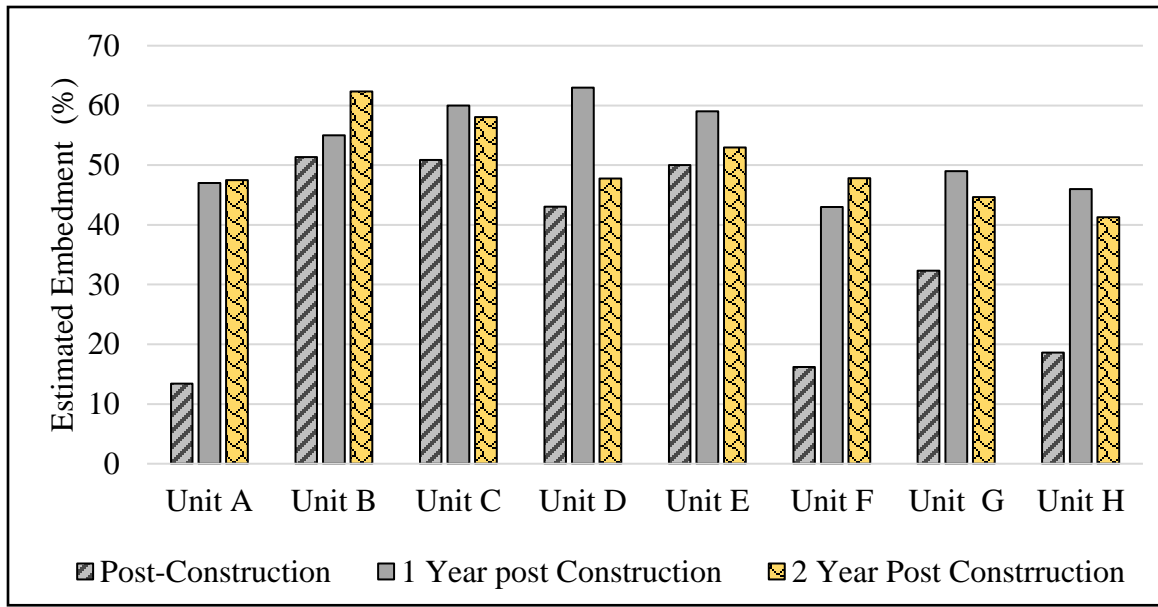
Figure 2-10 Embedment depth estimates

Dynamic friction test (Coefficient of friction- M_u)

Dynamic Friction Test (DFT) was used to measure the coefficient of friction, Mu, and is related to a pavement's microtexture properties. A DFT machine was purchased and samples were tested in the laboratory under dry and wet conditions. DFT testing scheme is shown in Figure 2-11. A DFT value obtained at 40 kph provides a reasonable average according to the literature. Figure 2-12 to Figure 2-16 represents DFT results for different units' test sections after one year and two-years post construction.

DFT results showed that hot-applied asphalt chip seal test sections had a slightly higher average M_u with lower variance compared to emulsified asphalt chip seal, when running the test in dry conditions. DFT data collected in the second year (2016) appears to be slightly higher than data collected in the first year (2015) in the dry condition for all studied test sections. In contrast, Units E, F and H exhibited lower Mu values at the second year compared to the first year in the wet condition. Units D, F and H exhibited the largest differences in their dry values between the first and second year observations.
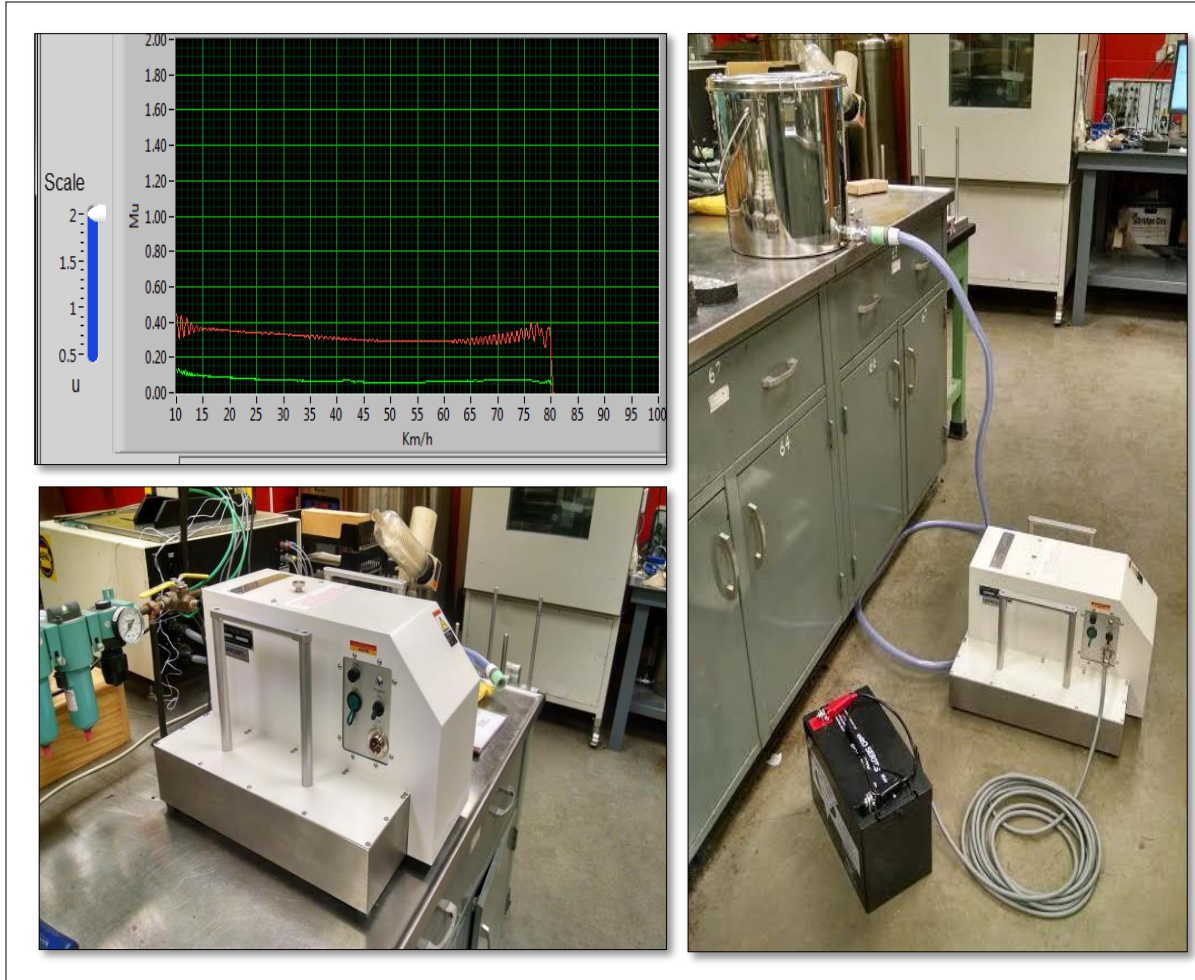
Figure 2-11 DFT equipment setting

New Zealand chip seal manual discusses the role of seasonal variations and precipitation on microtexture frictional surface measurements (*Chipsealing in New Zealand. Transit New Zealand* 2005). The manual explains that in summer with dryer periods, vehicles will grind down the rock and produce a fine flour, which acts as a polisher. In wet winter months, the small particle fines are washed away and the coarser grit is left on the roadway increasing skid resistance. The increase of winter skid resistance followed by the decrease in the summer creates a cyclical skid resistance pattern throughout the year. Oregon projects had a wetter winter in 2016 than 2015, and this explains the higher M_u values recorded for DFT (2016) testing when compared to M_u values recorded for DFT (2015) testing.
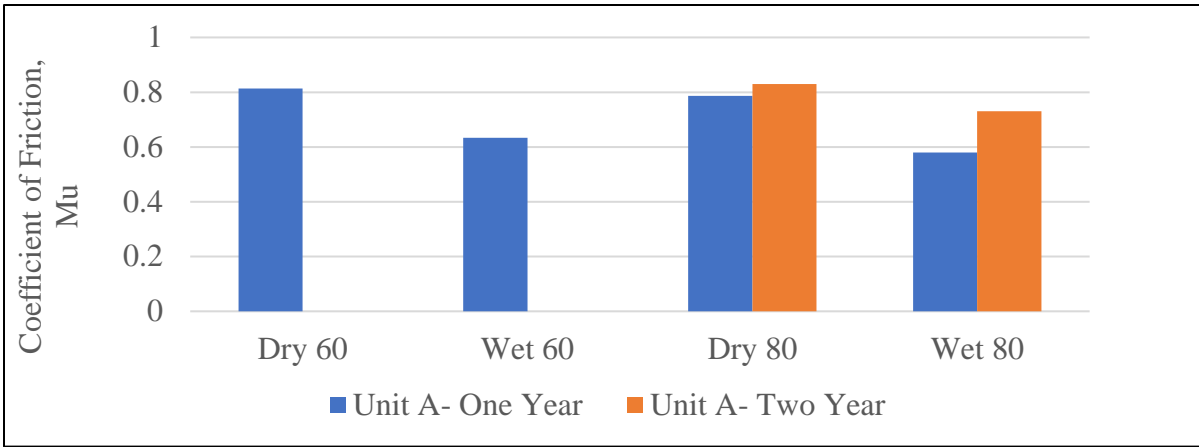
Figure 2-12 DFT results (Unit A)
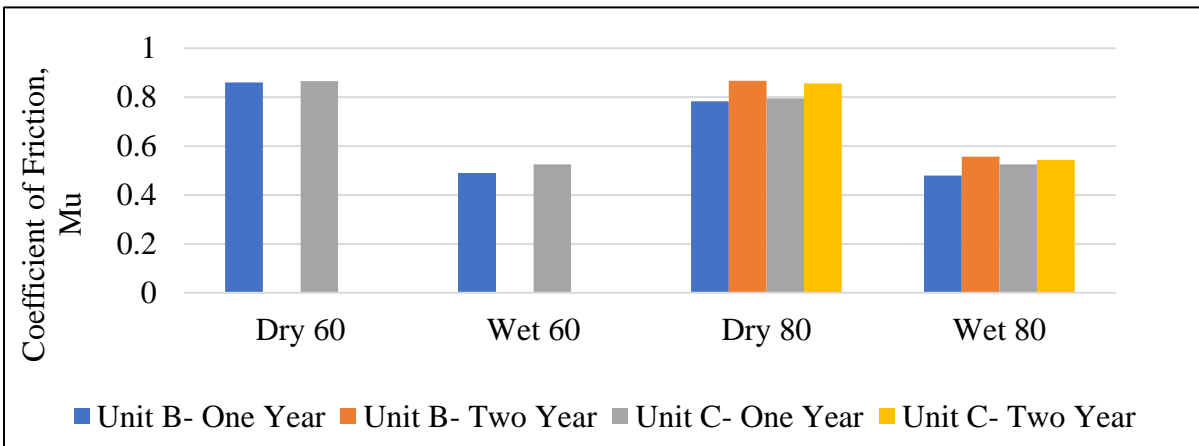
Figure 2-13 DFT results (Units B&C)
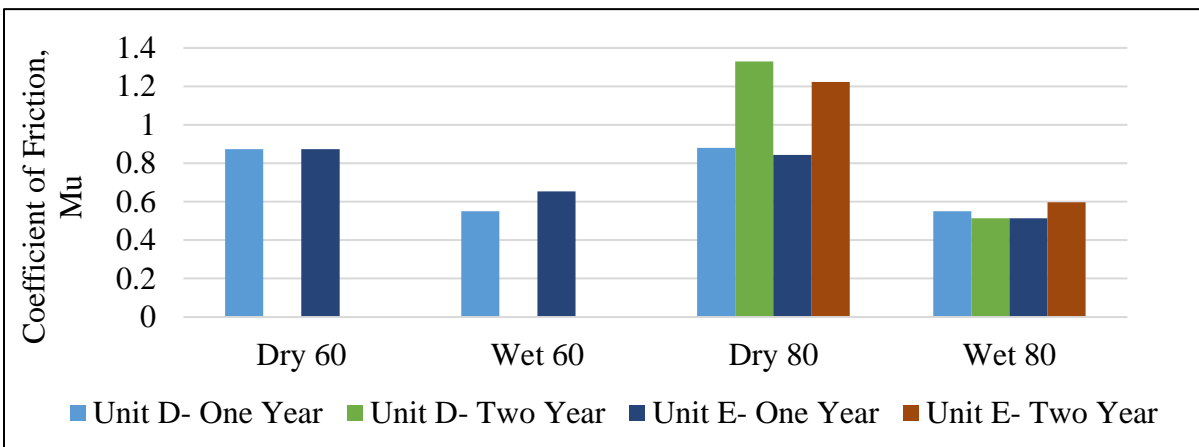
Figure 2-14 DFT results (Units D& E)
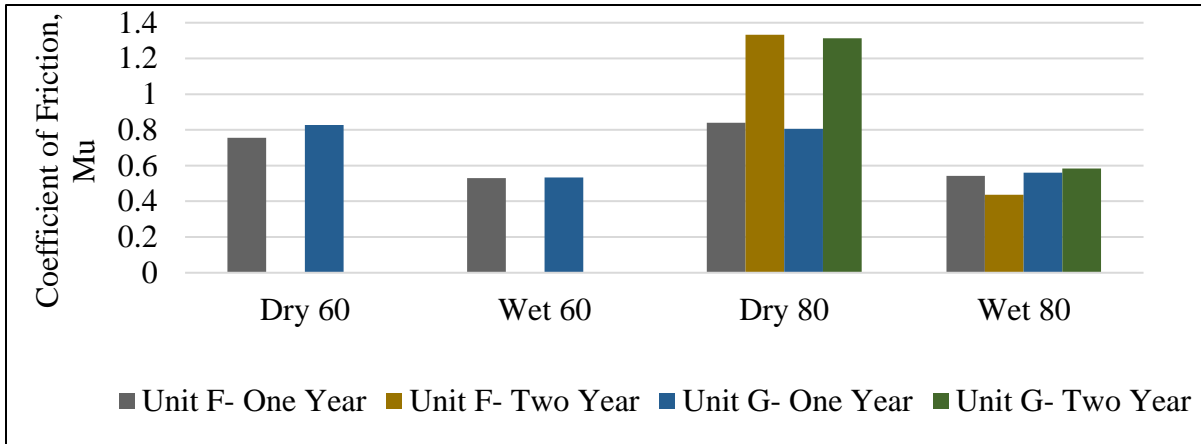
Figure 2-15 DFT results (Unit F)
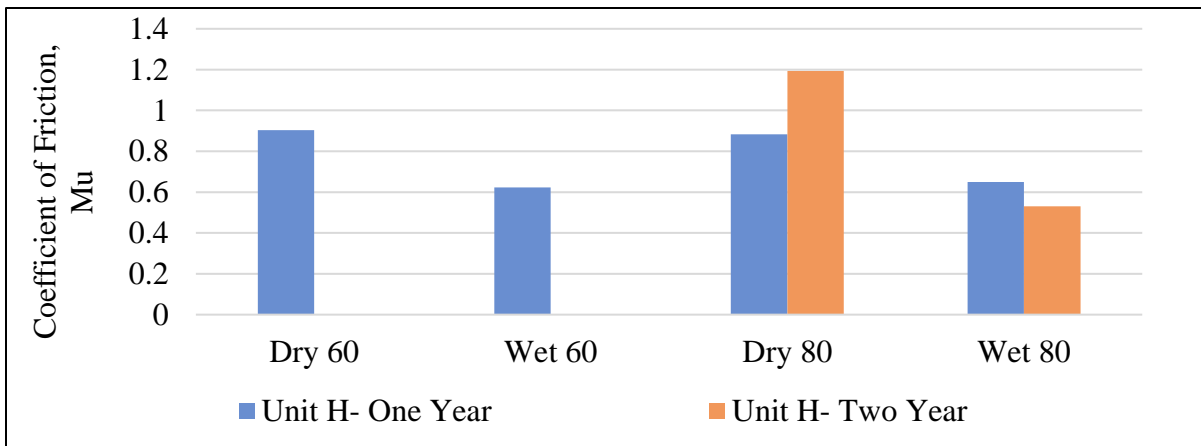
Figure 2-16 DFT results (Unit H)

2.3.3 Pavement condition assessment

Distresses in flexible pavements are an important consideration when selecting the most appropriate preservation and rehabilitation strategy. Primary structural distresses include fatigue cracking (alligator cracking), longitudinal cracking, and transverse cracking. Some DOT's, such as Utah DOT, have established pavement performance models that consider traffic volumes, pavement condition, construction history, costs, treatment strategy and funding scenarios to identify the best matching pavement preservation and rehabilitation project (Wilson and Guthrie 2012). Based upon the literature, the most occurring visible chip seal distresses are: oxidation, aggregate wear, aggregate polishing, bleeding, and aggregate

loss (Gransberg 2007). In this study, distresses in Oregon pavements test sections were documented and quantitatively assessed using a survey.

The research team conducted the condition survey manually to identify the distresses observed. For each pavement section, three-500 foot sections (152 meter) were surveyed, and the location of the crack within each section is recorded. The crack type is identified and relative data including length, width and/or area are recorded. Distresses data were observed at roadways pre-seal construction, one-year post seal construction and two-year post seal construction. Distress survey results are shown in Figures 2-18 to Figure 2-23.

The highest occurring distress in observed roadways is transverse cracking, with highest reoccurrence in Units A, C and F, bearing in consideration that they are emulsified based sections. Figure 2-17 shows that all roadways' transverse cracking length has decreased in the post-construction stage when compared to the pre-construction stage. In cases where no pre-construction transverse cracking was observed, no additional cracking has occurred after the placement of the chip seal. Units A, E and H are likely to reach their pre-construction cracking levels within three years, but chip seal has generally reduced overall cracking in all observed test sections.

Figure 2-18 displays longitudinal cracking results in each chip seal section. Longitudinal cracking was monitored at the preconstruction condition up to two-year post construction condition. Unit D showed the highest initial longitudinal cracking, but this was non-load related edge cracking. After chip seal treatment application, Unit D shows no longitudinal cracking at one-year and two-year post construction surveys. Overall, chip seal surface treatment decreased the total length of longitudinal cracking in all studied roadways. In addition, the change in longitudinal cracking length between one and two-years post

construction is considered minimal. Pavement condition surveys provide evidence that chip seal preservation technique has been effective in reducing the appearance of longitudinal distresses.
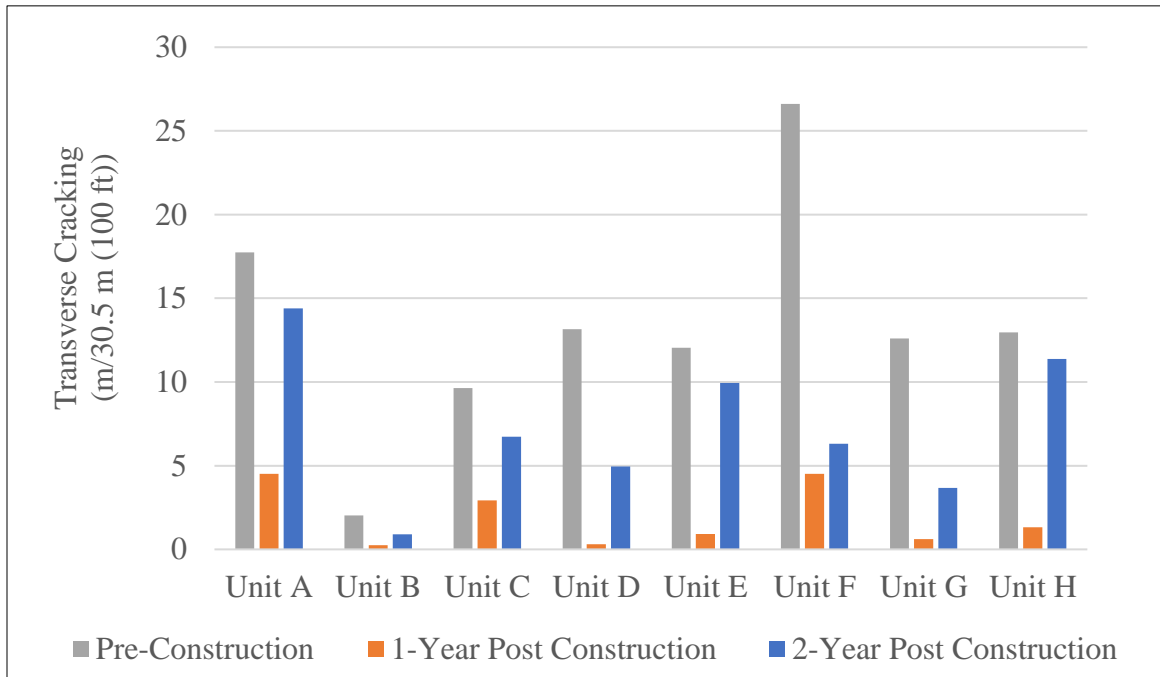
Figure 2-17 Distress survey results (transverse cracking)
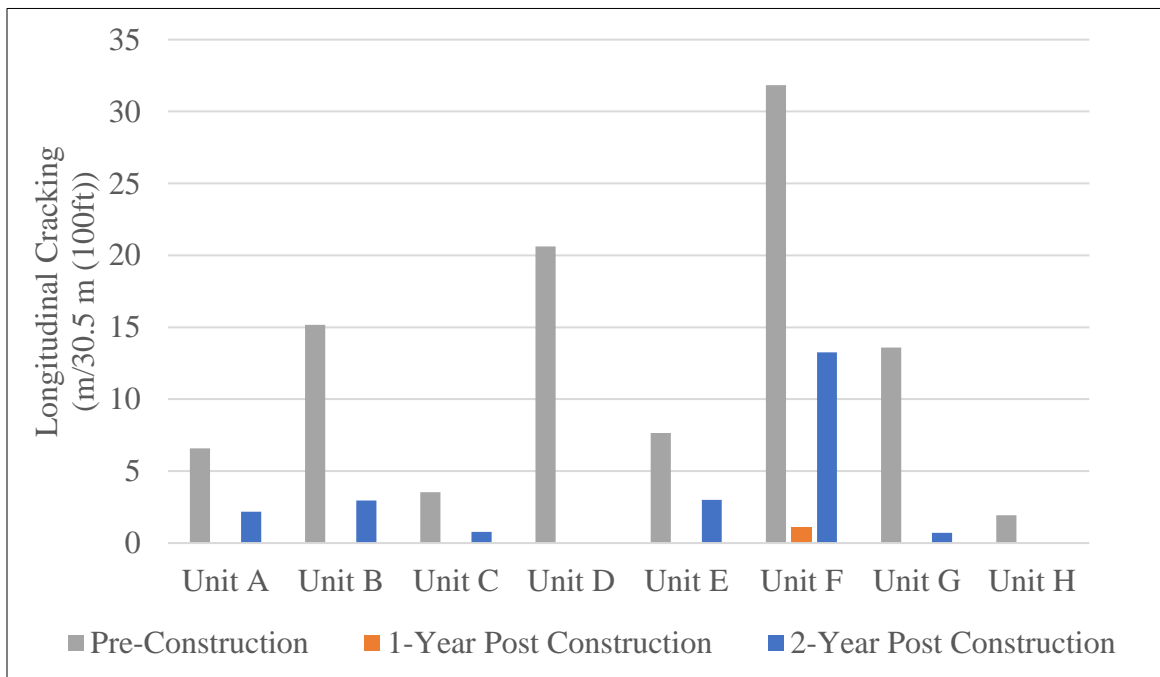
Figure 2-18 Distress survey results (longitudinal cracking)

Figure 2-19 shows results of fatigue cracking survey. Fatigue cracking was identified in all sections prior to chip seal placement, and no fatigue cracking was further observed in the follow up pavement surveys. This finding is significant in showing that chip seals are effective in preserving the pavement surfaces. On the other hand, Unit B exhibited the highest fatigue cracking before chip seal application. Unit B had the lowest MTD and M_u measurements, which reflected the poor underlying condition of the road. Yet, chip seal has helped reducing fatigue cracking over the two-year performance-monitoring period. The presence of fatigue cracks in roadways is often a pre-curser to potholes occurrence. Sustained reduction in fatigue cracking in roadways emphasizes the success of this preservation technique.
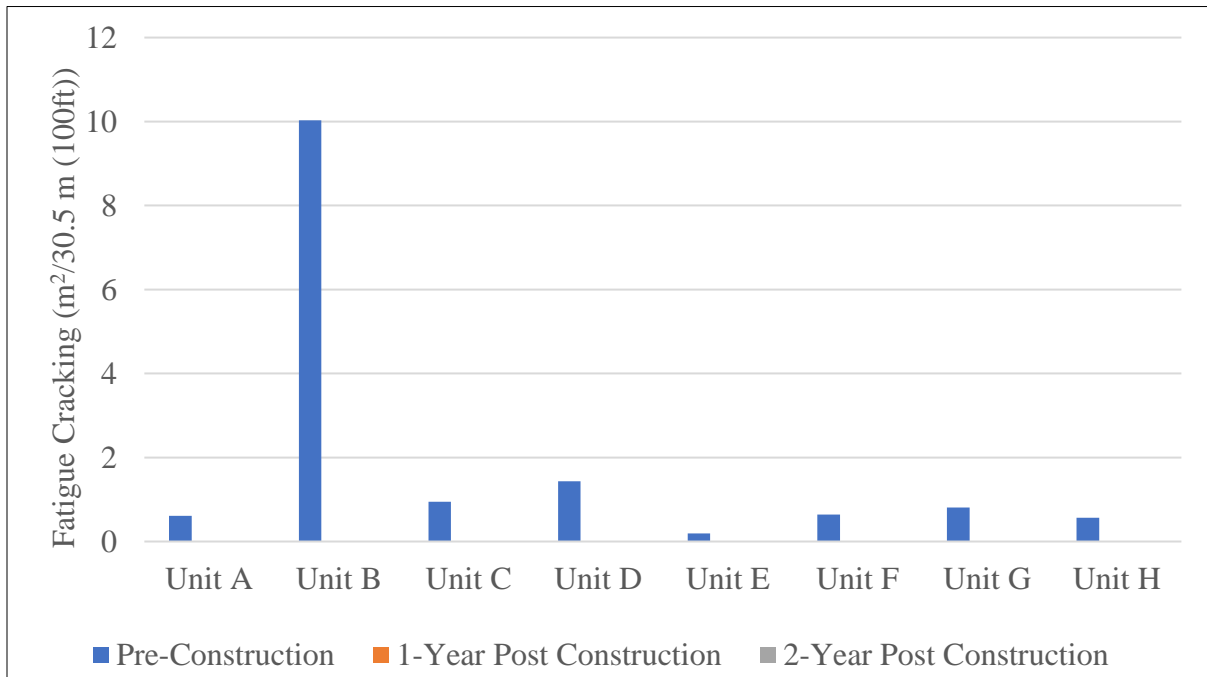
Figure 2-19 Distress survey results (fatigue cracking)

shows the effect of chip seal construction on reducing potholes for the roadways observed. Potholes were documented in Units F, G and H in few isolated areas. Patching was also observed in different units, and results are showed in .
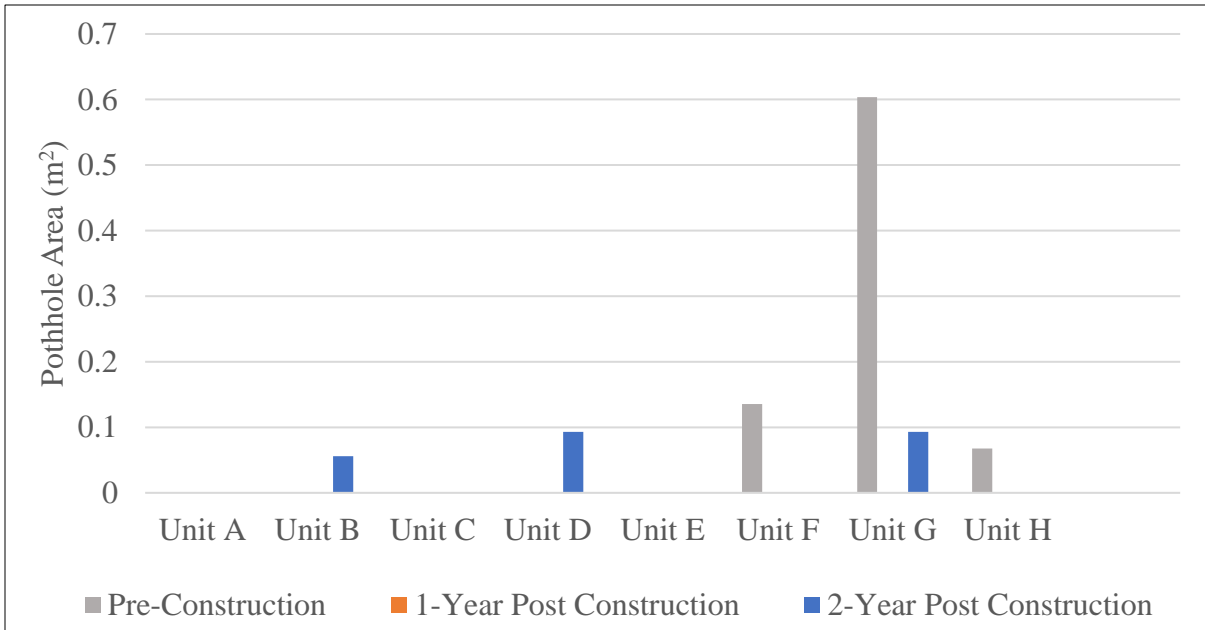
Figure 2-20 Distress survey results (potholes)
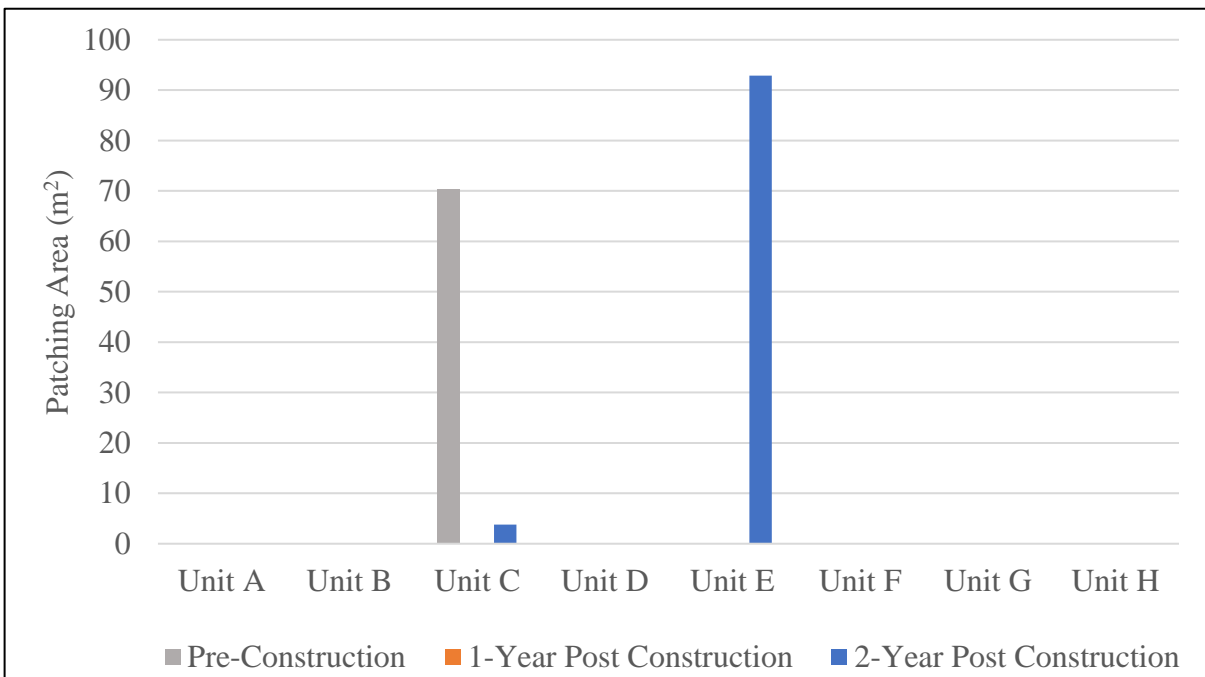
Figure 2-21 Distress survey results (patching)

No patching was observed/needed at one-year post chip seal application, except in

Unit C. There were extensive pre-seal patching works done on Unit C, which required re-

patching between one and two-years post construction. Based on this observation, chip seal

application did not preserve patching in the distressed wheel paths. This shows that the pre-seal condition of the roadways is highly linked to the overall deterioration of the seal.

Loss of aggregate and bleeding are chip-seal related distresses that usually lead to a marked reduction in texture properties. Figure 2-22 reports that Units C and E exhibited loss of aggregate at one-year post construction, while Unit G exhibited loss of aggregate at two-year post construction. Unit C exhibited loss of aggregate mostly in the wheel paths, as this was the section with the initial distressed and patched wheel paths.

Figure 2-23 shows bleeding distress over the two years monitoring period. Bleeding started to appear after 2-years of roadway construction in Units B, D and E, with Unit B having the highest bleeding level, which can be related to its initial road condition with the lowest pre-seal MTD, which did not pass the performance specification requirement.
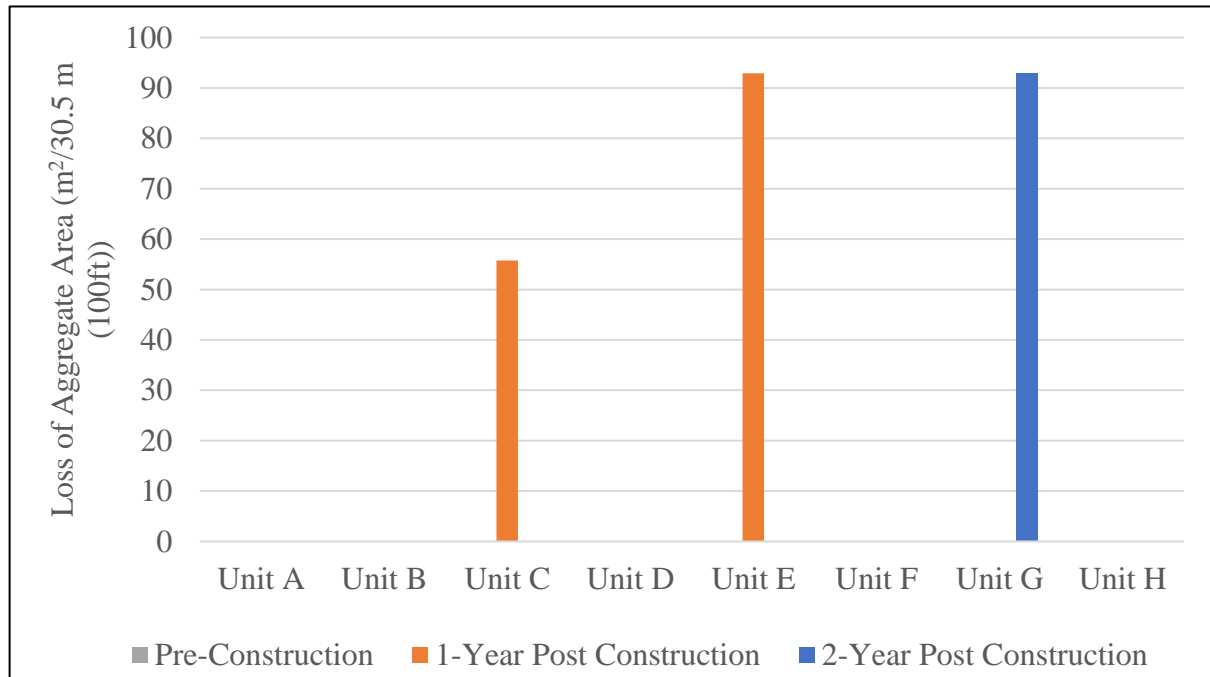
Figure 2-22 Distress survey results (loss of aggregates)
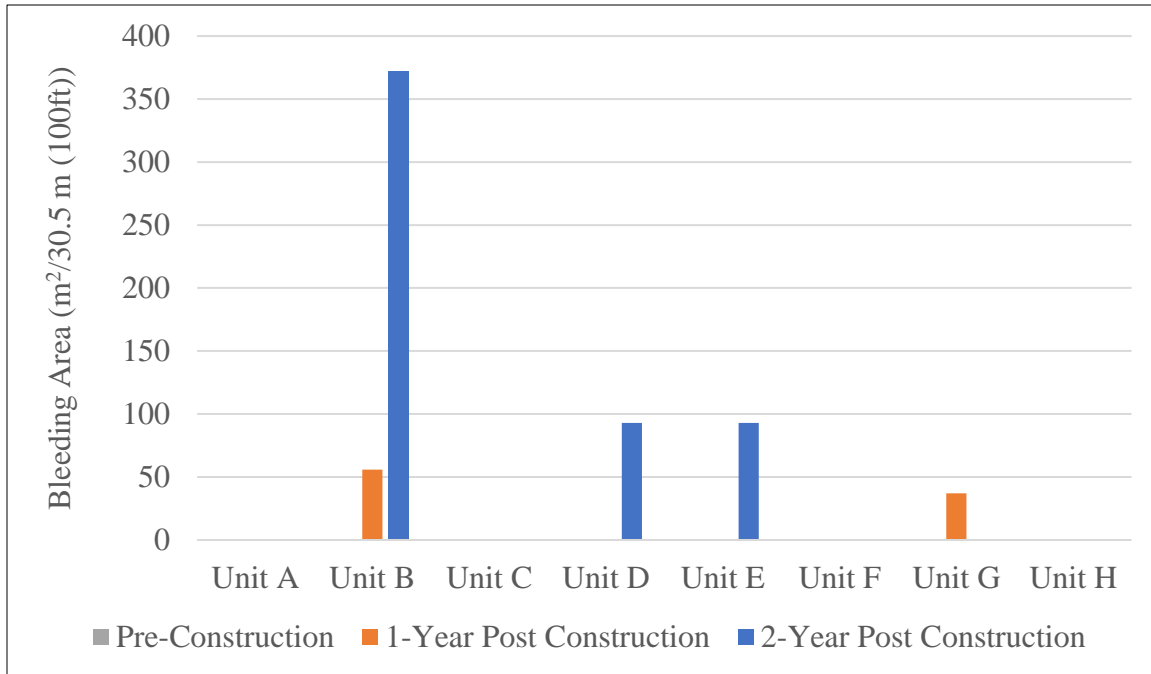
Figure 2-23 Distress survey results (Bleeding)

From results, one can conclude that both hot-applied asphalt and emulsified asphalt chip seal application have led to an overall improvement of all monitored pavements condition. Chip seal preservation techniques can serve as a highly performing pavement maintenance option. Chip seal is capable of providing a durable functional pavement surface, when constructed properly.

2.4 Conclusions

The study uses different testing schemes to understand the performance of chip seal pavements and question its effectiveness. Three major considerations were discussed which are laboratory testing, field performance investigations and standards specifications. All these considerations were tied up together to present a holistic view of chip seal performance evaluation.

A case study of eight chip seal roadways was used to validate the approach of the study. Aggregates used in all test sections have proven to be of good quality concerning

gradation, flakiness and abrasion resistance, and met the ODOT specifications. Performance of observed roadways verified that chip seals constructed with both hot-applied and emulsified asphalt binders have yielded satisfactory performance regarding their pavements' microtexture and macrotexture properties for the two years monitoring period. Chip seal application have reduced the occurrence of visible cracks in all studied roadways, and reduced potholes occurrence. In contrast, chip seals did not preserve patching in distressed wheel paths, as recorded in Unit C which required re-patching after two-year post construction. Loss of aggregate cover was identified in Units E, C and a small section in Unit G. Bleeding was mainly observed in Unit B. These chip seal related distresses occurred mostly in the wheel path with allowable limits.

Overall, chip seal treatments were found effective in preserving pavements surface from further cracking and deterioration and improving the surface macrotexture during two-year evaluation period. The study further attributed the performance of chip seal to many factors including pre-seal condition of the pavement, traffic volume and type and quality of used materials.

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CHAPTER 3. CHIP SEAL AGGREGATE EVALUATION AND SUCCESSFUL ROADS PRESERVATION

Modified from a paper published in Construction and Building Materials

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Abstract

The Federal Highway Administration's Every Day Counts (EDC) initiative focuses on saving time, resources and money. EDC has brought infrastructure preservation to the forefront of many conversations. Chip seals are a cost-effective pavement preservation strategy, and continued studies verifying their performance benefits continue to be in high demand as agencies struggle to fund preservation programs. The study documents the effect of aggregates properties, binder type, existing roadway and construction conditions influence on the overall chip seal performance. A comparative analysis between hot applied and emulsified asphalt chip seal treatments through gathering two years of field performance data (June 2014 to June 2016) from chip seal projects constructed in Oregon is performed.

Findings show that aggregate size, shape, gradation and toughness are key elements to ensure chip seal success. Both hot applied and emulsified test sections had experienced improvements in their microtexture and macrotexture properties after chip seal application. Emulsified test sections had more improvements in their texture properties immediately after construction in comparison to the hot applied test sections. However, after one year in-service, emulsified asphalt sections lost texture resulting in having both seal types with similar MTD by the two-year pavements operation. In addition, roadways initial condition have significantly affected chip seal performance and that was reflected on their mean texture depth results as well as distresses observed.

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3.1 Introduction

3.1.1 Background

Aristotle is credited with saying, "*The whole is greater than the sum of its parts*" and for chip seals, this is particularly true. Chip seal is a system of binder and chips placed in a single layer (or multiple layers) that are working together to preserve the underlying pavement structure. Chip seal aggregates, binders, existing roadway and construction conditions influence the overall chip seal performance. When all parts come together in an engineered system, the result is one of the most cost-effective ways to preserve asphalt pavements (Gransberg and Zaman 2005).

This paper summarizes the results of a study that investigated ways to improve chip seal specifications in Oregon. Throughout the project, materials used in construction met or exceeded specifications, good construction practices were followed and agency involvement occurred throughout the duration of the research; as a result, this study presents several years of data showing that with best practices, chip seals meet performance expectations and successfully preserve roads.

Roads in the US are considered major public investments. In 2007, Texas Transportation Institute released a special report documenting that poor serviceability and roadways reconstruction costs America nearly 78 billion US dollars annually by means of wasted time, services and fuel (Reid 2008). As a result, highway agencies have been interested in preserving highway investments through research and field investigations (Galehouse et al. 2003). The World Bank's pavement deterioration model has further shown that the amount of money required to restore existing deteriorated pavements to their initial state costs four times more than using preventative construction methods (Wilde et al. 2014).

One of the most commonly used preservation techniques is chip seal. There are many different types of chip seals, including: single chip seal, multiple chip seal, racked in seal, cape seal, inverted seal, sandwich seal and geo-textile reinforced chip seal, with the most common type being the single layer chip seal (Gransberg and James 2005). The type of chip seal used depends on the existing pavement's structural condition, roadway geometry, expected traffic volume, initial cost and lifecycle costs (Transit New Zealand 2005). Chip seals effectively extend the pavement performance life in the following ways (Gransberg et al. 2010a; WSDOT 2015):

- Reduces roadways maintenance costs,

- Improves skid resistance,

- Prevents water paths into the roadway substrate,

- Seals cracks,

- Provides anti-glare surface,

- Increases the reflective surface for night and wet driving, and

- Reduces oxidation and aging effects

Chip seal research has advocated for performing chip seal designs prior to construction to determine the initial chip and binder application rates. McLeod design method is the most commonly used chip seal design guideline in the United States, while New Zealand design method provides the most comprehensive chip seal design guide used internationally. Both McLeod and New Zealand designs consider traffic and surface conditions as factors (McLeod et al. 1969; Patrick and Donbavand 1996).

During design, aggregate properties such as gradation, flakiness index, specific gravity, absorption and the average least dimension (ALD) are measured. If a uniform

gradation is used, the aggregate's ALD should represent the chip seal coat thickness in consideration of traffic effect on the aggregate embedment and orientation (Kutay and Ozdemir 2016).

3.1.2 Chip seal laboratory and field investigations

Chip seal performance is greatly affected by the aggregates properties, the type of asphalt binder and the relative amounts of each (Li et al. 2012; Visintine et al. 2015). The most influential properties are aggregate size, shape, gradation, cleanliness and quality of asphalt. Chip seal design should also consider many on-site factors that affect the actual pavement performance.

Research has shown that existing pavement conditions and environmental factors have the most influence on performance (Gransberg et al. 2010a; Henning et al. 2014; Schlotjes et al. 2013). Studies have revealed that applying chip seals on poor substrate road conditions results in poor performance and a decreased expected life span (Hajj et al. 2010; Henning et al. 2004). Environmental factors that mostly affect chip seal performance are climate and weather (Wilson and Guthrie 2012).

Aggregate testing is essential to evaluate chip seal performance. Aggregate imaging systems (AIMS) scheme is considered vital for the analysis of aggregates properties. AIMS equipment takes a series of aggregate images and analyzes them using an imaging software. AIMS testing is able to quantify the aggregate properties related to angularity and sphericity (Gransberg et al. 2005). Such properties affect the quality of the bond between the aggregates and the binder. Masad et al. compares AIMS measurements to other commonly used aggregate analysis methods, and the research concluded that AIMS testing produces more easily utilized results that better resemble the actual field performance (Mahmoud et al. 2009).

Field investigations are necessary to investigate chip seal performance and ensure its success. Indicators such as surface texture properties are usually manipulated to assess chip seal performance (Gransberg and Zaman 2005). Surface texture represents both micro-texture and macro-texture properties of the pavements. Micro-texture is a function of the frictional properties of the aggregate itself, while macro texture is a function of the aggregate's size, shape, and gradation (Pidwerbesky et al. 2006). Mean texture depth (MTD) and mean profile depth (MPD) are the most widely used field measurements to represent the surface macro-texture properties. Sand circle test is usually advised to measure the MTD which follows New Zealand specifications (Hall et al. 2009). Research has shown that sand circle test is equivalent to sand patch test which follows ASTM E965 (TNZ 1981). Dynamic friction test (DFT) is commonly used to represent the surface micro-texture properties by measuring the coefficient of friction.

3.1.3 Pavement field condition

Pavement condition assessments are utilized to quantify pavement performance over time. Pavement condition is primarily assessed based upon apparent distresses (Aktas et al. 2013).Distresses are usually investigated visually and/or quantitatively. Primary structural distresses include fatigue cracking (alligator cracking), longitudinal cracking and transverse cracking. Representative sample roads are usually selected at various traffic volumes and underlying conditions and related data is collected, processed and analyzed for different years to be used for future performance evaluation and planning. Chip seal predominant related distresses are oxidation, aggregate wear, aggregate polishing, bleeding, and aggregate loss (Gransberg 2007).

Distress surveys have been one of the most common ways to evaluate overall chip seal performance. Some agencies have established visual performance criteria for chip seal performance evaluation. Some criteria include (Ohio Department of Transportation 2016):

- Chip seal surfaces should have minimal tears and streaks,

- Joints should be neatly constructed and free of any built up or irregularities,

- Longitudinal joints should have no more than a 2 inch (50 mm) overlap,

- Edges should be neat and free of irregularities, and

- A maximum variance of 2 inches (50 mm) per each 100 feet (30.5 m) is permitted

3.1.4 Objectives and scope

The objective of this research is to build and expand on existing research that advocates for quantitative test results. The paper provides data to establish straightforward field measurements that offer an indication to the effect of different parameters (aggregates properties, binder type, existing roadway condition) on chip seal performance.

The paper uses: (1) laboratory testing, (2) field testing and (3) performance monitoring to reach the objectives of the study. Laboratory testing uses traditional aggregate testing settings in addition to AIMs aggregate testing scheme to assess the properties of used aggregates including angularity and sphericity parameters, which are essential for chip seal evaluation.

Field-testing included measurements of MTD and friction parameters using sand circle test (TNZ T/3:1981) and dynamic friction test (ASTM E670 – 09: 2015). Pavement performance surveys evaluated pavement distresses before chip seal application, immediately after seal application, after one year and two years of traffic/in-service life. Distresses were

identifies according to distress identification manual for long term pavement performance and Oregon DOT distress manual guideline (Miller and Bellinger 1989; Oregon Department Of Transportation 2010).

3.2 Projects Overview

The project included in this study was constructed in 2014 and is located in the state of Oregon. Table 3-1 and Table 3-2 summarize the different test sections (denoted as units A to H) with their relative information, such as: location, binder types, traffic flow (annual average daily traffic AADT) and initial road condition. Binder types includes polymer modified emulsified asphalt (CRS-2P) and polymer modified hot applied asphalt (AC-15P). Traffic flow represented both low volume traffic roads with less than 500 AADT, and high volume traffic roads with more than 500 AADT. Existing pavement condition varied from very poor to good based upon ODOT provided pavement condition data.

Units B and C had poor underneath pavement condition, while unit D had good initial pavement condition. The surface of the pavements were generally slightly pocked, porous, and oxidized. Crushed stone (granite) and gravel were used in the test sections. Units B, C, D, and E had aggregates from the same source quarry; similarly, units F and G had aggregates from the same source quarry. Aggregates used for hot applied chip seal roadways were pre-coated in accordance with best practices recommendations (Gransberg and Zaman 2005). Pre-coating includes the application of a thin film of bitumen (Asphalt) to the aggregates. The asphalt film reduces surface dust and provides better adhesion to the hot asphalt.

Table 3-1 Oregon projects (hot-applied seal) information summary

Test Section (unit)	B	C	D	E
Location	OR - 140	OR - 66	Trig.Ln./Miller Isle	OR - 140
Seal Type	AC- 15P	AC- 15P	AC- 15P	AC- 15P
AADT	2300	2900	1280	1345
Pre-seal condition	Poor	Poor	Good	Fair

Table 3-2 Oregon projects (emulsified seal) information summary

Test Section (unit)	A	F	G	H
Location	OR - 62	Hwy-50	OR - 70	OR - 31
Seal Type	CRS- 2P	CRS- 2P	CRS- 2P	CRS- 2P
AADT	460	2650	670	690
Pre-seal condition	Fair	Poor	Fair	Fair

A key consideration in chip seal application is the climate. Chip seal construction favors dry, mild weather conditions. According to the United States Department of Agriculture, Oregon's climate is generally cold in winter and mild in summer, ranging from 30 to -25 °C, with frequent rain throughout the year. Oregon's Department of Transportation current specifications limit chip seal construction season to July through August based only on climatic reasons. The surface temperatures and quantities of used materials were measured during construction. The data verified that the contractor abided by Oregon chip seal specifications.

Each roadway was divided into three 500-foot test section, where fifteen measurement points were identified for field evaluation. Periodic testing was conducted, and included sand circle test (TNZ 1981) and dynamic friction test to determine texture changes on each point along two years monitoring period. In addition, distress surveys were conducted to monitor deterioration along the same two years period.

3.3 Experimental Work Results

3.3.1 Aggregates general properties

Aggregates were tested to determine their physical properties including specific gravity, density and percent absorption. Bulk specific gravity (SSD) varied from 2.58 to 2.67, and apparent specific gravity ranged from 2.67 to 2.76. The water absorption of the aggregate chips ranged from 1.63 percent to 2.65 percent. These properties are all within acceptable specification limits.

Aggregates gradations were obtained by performing sieve analysis and are shown in Table 3-3. Uniform gradation is ideal for chip seals (Patrick and Donbavand 1996). Based upon results, all units acquired uniformly graded aggregates, with unit H having the most uniform gradation.

Table 3-3 Aggregates gradation properties

	Sieve size		Percent Passing Cumulative							
	inch	(mm)	Unit A	Unit B	Unit C	Unit D	Unit E	Unit F	Unit G	Unit H
Gradation	1"	25	100	100	100	100	100	100	100	100
	3/4"	19	100	100	100	100	100	100	100	100
	1/2"	12.5	100	100	100	100	100	100	100	100
	3/8"	9.5	93	82	82	82	82	89	89	93
	#4	4.75	26	5	5	5	5	12	12	11
	#8	2.36	1	1	1	1	1	1	1	2
	#16	1.18	1	1	1	1	1	1	1	2
	#30	0.6	1	1	1	1	1	1	1	2
	#50	0.3	1	1	1	1	1	1	1	2
	#100	0.15	1	1	1	1	1	1	1	2
	#200	0.08	1	1	1	1	1	1	1	2
Flakiness Index (%)			13.1	5.2	5.2	5.2	5.2	6.4	6.4	12.1
Aggregate Loss (%)			6.1	7.2	7.2	7.2	7.2	7.5	7.5	8.6
PUC			0.4	0.2	0.2	0.2	0.2	0.1	0.1	0.1

Aggregates were also examined for flakiness and toughness properties. Generally, all aggregates have passed the flakiness and abrasion acceptable specification limits. Flaky or elongated particles are not preferred for chip seals, as they tend to break down and/or dislodge, which contributes to bleeding and aggregate loss within the seal. Best practices recommend limiting the amount of flaky particles to 25 percent (Li et al. 2012). Micro-Deval testing was performed to examine the aggregate loss due to frictional and impact forces. ODOT specifies a maximum acceptance limit of 40 percent of aggregate loss to ensure a durable chip seal performance (Zaman et al. 2014). Unit A had the highest FI at 13.1 percent, and unit H had the highest aggregate loss of 8.6 percent, satisfying the performance specifications.

According to Broughton et al. (Broughton et al. 2012), as the PUC value approaches zero, the aggregate size becomes increasingly uniform. Smaller aggregates than the average size contribute to bleeding, while oversized aggregates usually contribute to aggregate loss. Zaman et al. (2014) sets a PUC maximum acceptable value of 0.2 for an improved chip seal performance. Most aggregates had acceptable PUC values, except unit A that had a value of 0.41.

3.3.2 AIMS laboratory testing

AIMS testing provides several useful parameters for determining aggregate shape and texture. In this study, aggregates' angularity was measured to assess their shape and sphericity properties. The gradient angularity index represents the sum of all angular values for points around the edge of the aggregate particle, and this index ranges from 0 to10,000. AIMS specifications categorize aggregate shape into four groups: (1) rounded, if their values are less than 2100; (2) sub-rounded, if their values lie in the range of 2100 to 4000; (3) sub-angular, if their values lie in the range of 4000 to 5400; and (4) angular, if their values are

higher than 5400 (Masad and Fletcher 2005). Figure 3-1 to Figure 3-4 represents the results

of AIMS analysis for each source aggregates retained on 3/8 inch and No. 4 sieves.
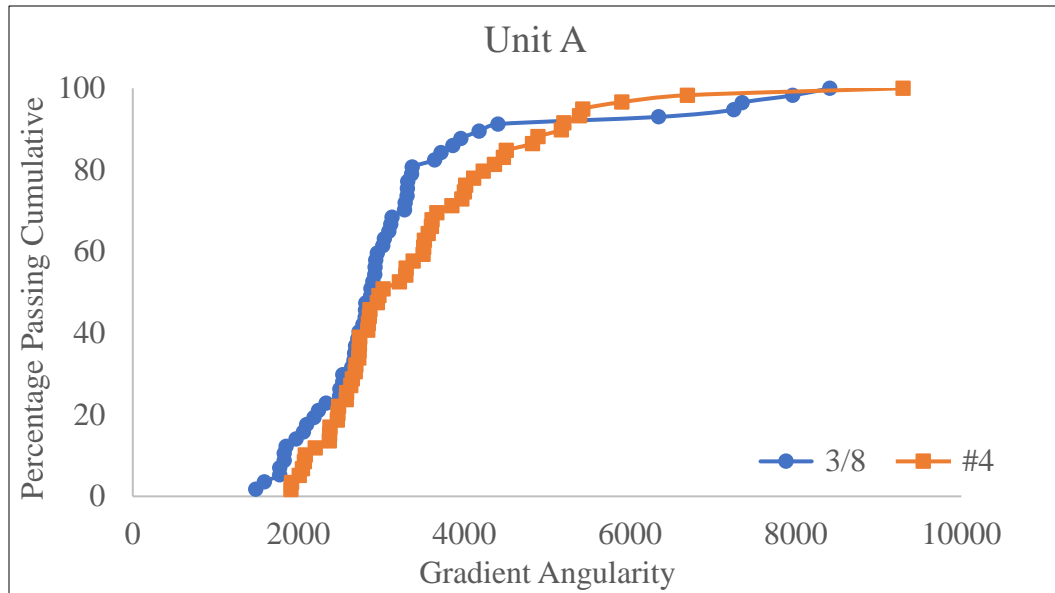
Figure 3-1 Gradient angularity (Unit A)
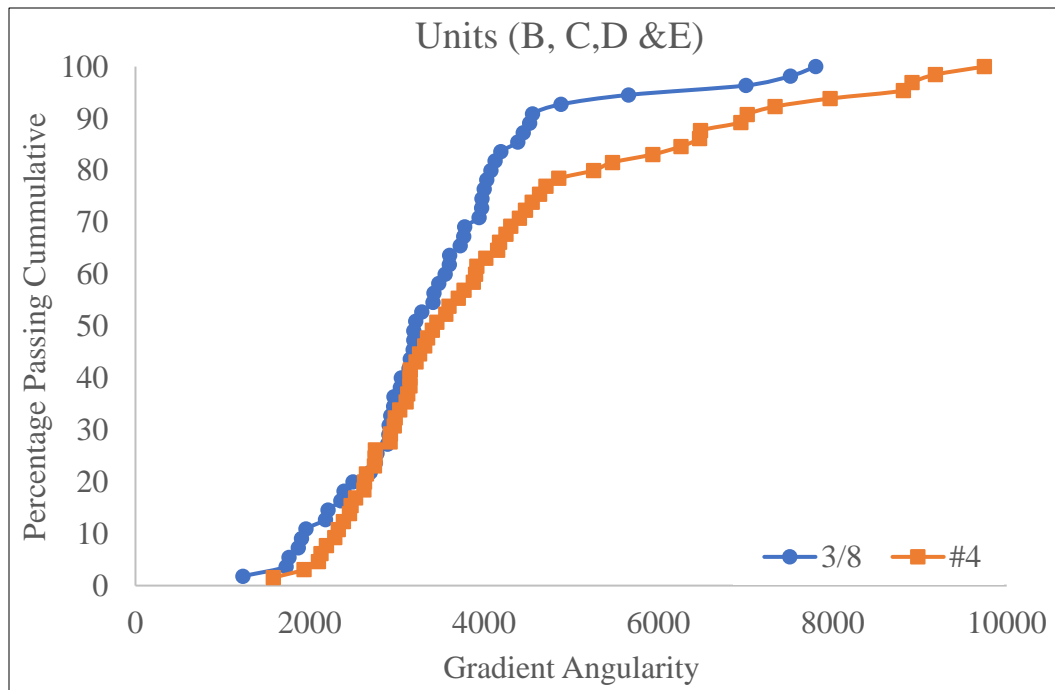
Figure 3-2 Gradient angularity (Units B, C, D & E)
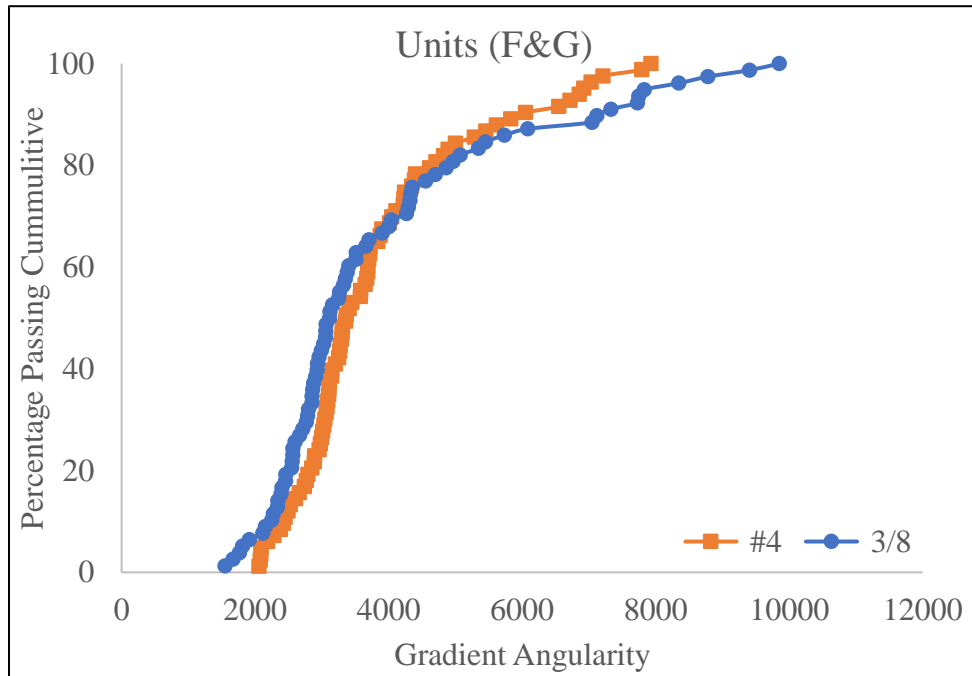
Figure 3-3 Gradient angularity (Units F & G)
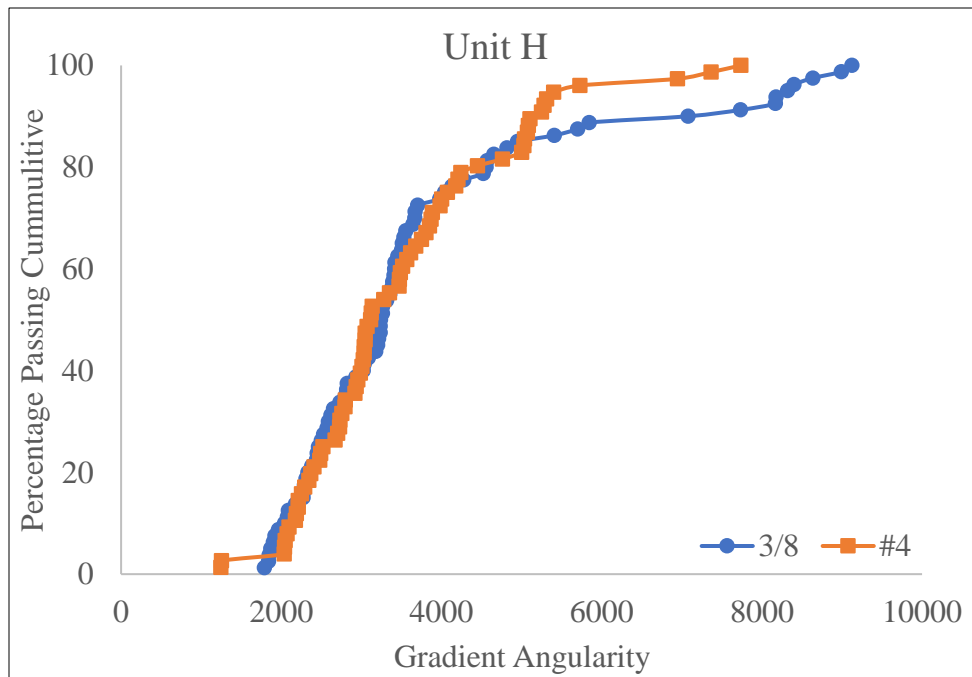
Figure 3-4 Gradient angularity (Unit H)

Results show that the average gradient angularity of both sieve sizes were relatively similar

with a value of 3600, which is in the sub-rounded aggregates range, and is expected to

exhibit good interlock (Zaman et al. 2014).

Sphericity is another parameter measured using AIMS laboratory testing, and provides a measure of aggregates shape. This is represented numerically in the range of 0 to 1, where 1 represents a perfect cube. Figure 3-5 graphically represents the different sphericity indices for each source aggregate retained on sieve 3/8 inch.
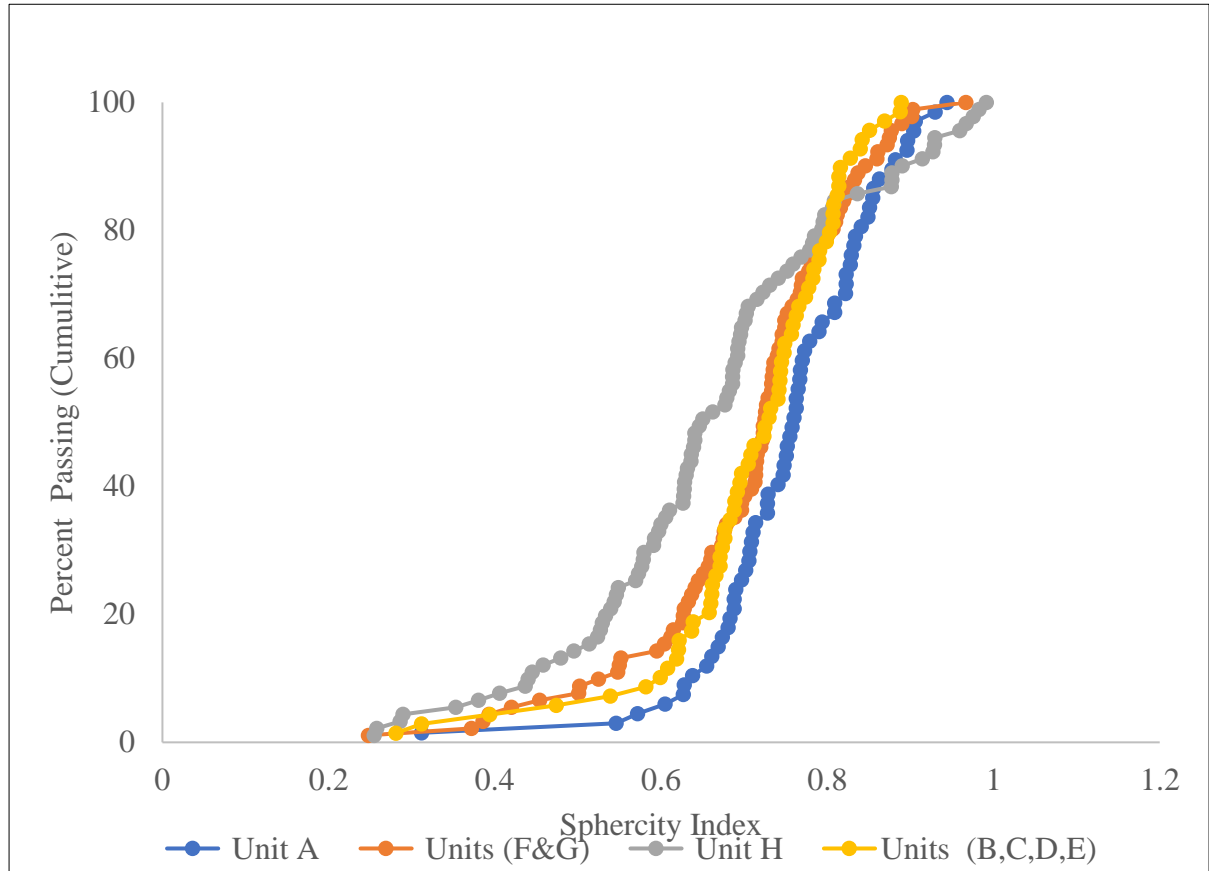
Figure 3-5 Klamath Falls aggregates Sphericity index

AIMS specifications categorize aggregates shape into four groups based upon their sphericity index: (1) aggregates that are more flat/elongated, if their values are less than 0.6; (2) aggregates with low spherical particles, if their values lie in the range of 0.6 to 0.7; (3) aggregates with moderately spherical particles, if their values lie in the range of 0.7 to 0.8; and (4) aggregate with highly spherical particles, if their values are higher than 0.8 (Masad and Fletcher 2005).

Results from the eight sections show that most of the aggregates' sphericity indices lie in the range of 0.7 to 0.8. This shows that all test sections have most of their aggregates with moderate sphericity, and thus are expected to form good wearing surface when placed on the binder.

Performed laboratory testing have shown that aggregates used in Oregon project have sustained successful/acceptable performance regarding gradation, flakiness, abrasion, angularity and sphericity properties. The aggregate testing validated that the materials used in the field were meeting or exceeding specifications. The next section is devoted to chip seal surface texture field examination.

3.3.3 Sand circle testing

Chip seal aggregates and binder work together to enhance the pavement's surface texture characteristics. The surface texture is critical in providing pavement friction properties. In this study, MTD is assessed using New Zealand sand circle test procedure (Hall et al. 2009). A recommended minimum MTD of 0.9 mm (0.04 inch) ensures adequate surface texture requirements. Figure 3-6 and Figure 3-7 represent MTD measurements between the wheel paths (BWP) at pre-construction, immediately after construction, one-year post-construction, and at two-year post-construction conditions. Various studies have used similar MTD performance trends along time to evaluate chip seal performance, and predict their lifetime accordingly (Aktaş et al. 2013; Gransberg et al. 2010b; Gransberg 2007; Pittenger and Gransberg 2012). Such studies confirmed that MTD measurements are an objective and accurate indicator of chip seal pavements performance.

Results demonstrate that chip seal application has led to improvements in the MTD measurements for all roadways. Emulsified test sections have experienced more improvements in their texture properties immediately after chip seal application in

comparison to the hot applied seal sections. However, after one year in-service, emulsified asphalt sections lost more texture resulting in having both emulsified and hot applied sections with similar MTD after two-years of pavements service
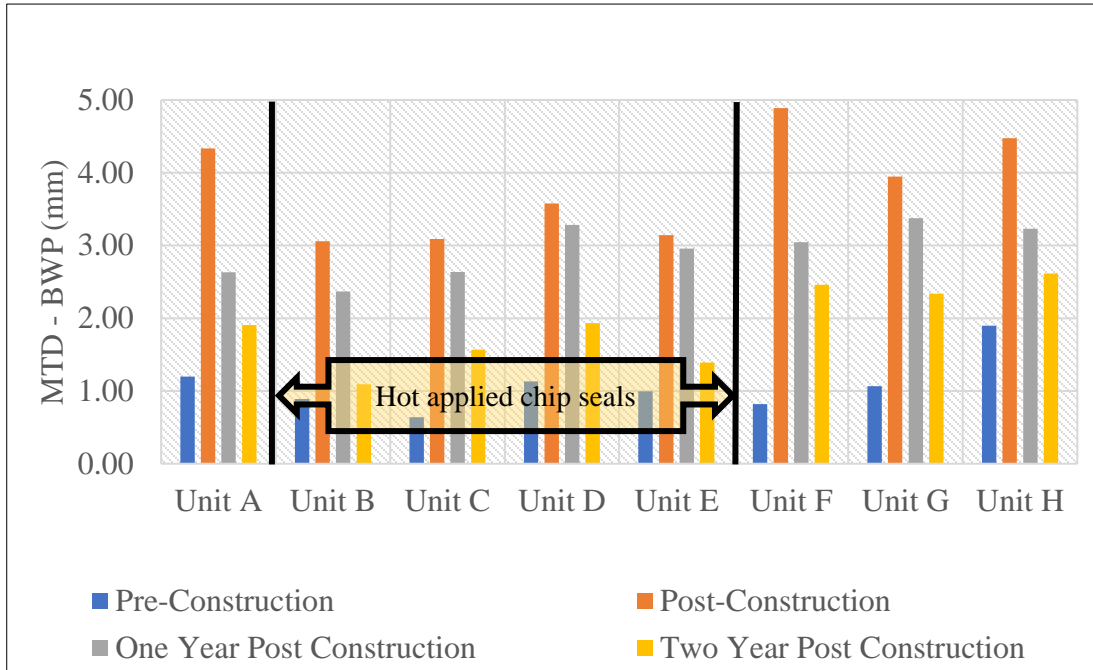
Figure 3-6 MTD comparative analysis results
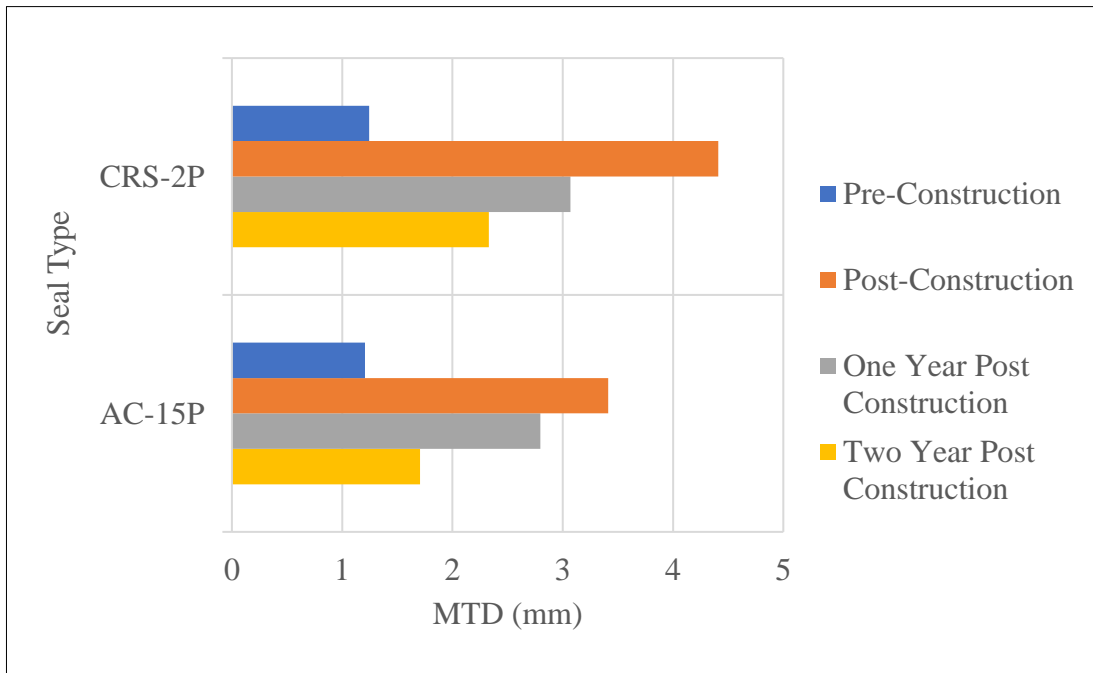
Figure 3-7 Effect of seal type on roadways MTD performance

Figure 3-8 shows the effect of pre-seal road condition on the MTD performance. Roadways with poor underlying road condition, (Units B, C and F), had the poorest surface texture performance at their pre-construction performance, failing New Zealand minimum accepted criterion of 0.9 mm. After the application of chip seal, all constructed units have passed the minimum criterion throughout their two-year' service life, yet roadways with poor underlying road conditions continue to exhibit lower performance when compared to the other roadways. Good and fair underlying road condition roadways have always exhibited an enhanced performance.
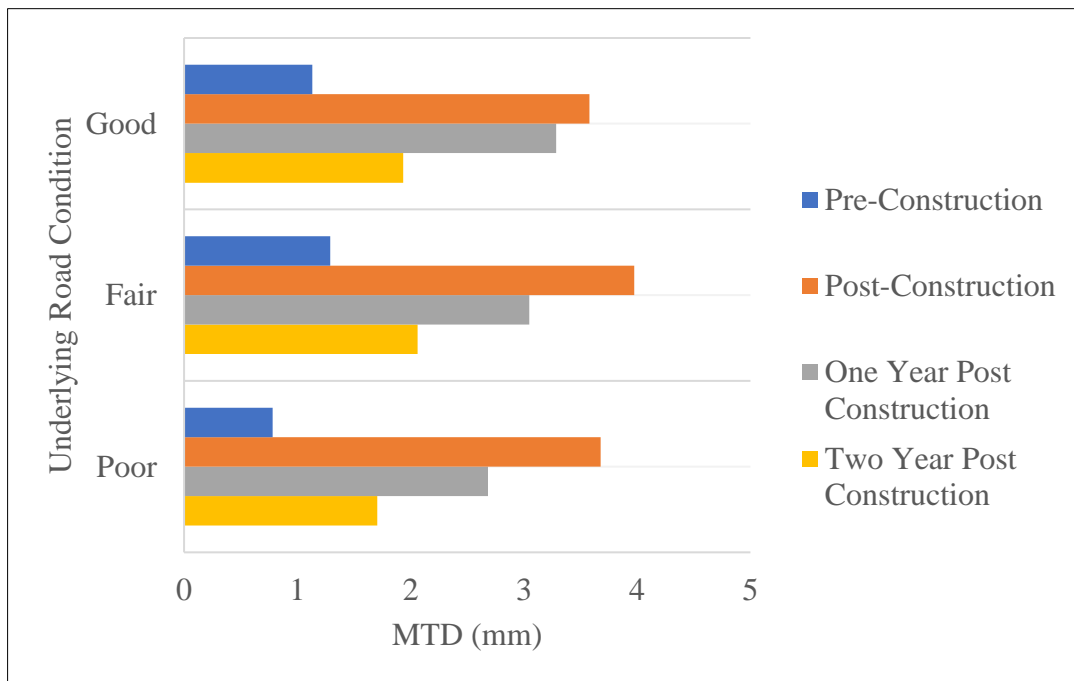
Figure 3-8 Effect of underlying condition on roadways MTD performance

The study assessed the possible effect of traffic on the MTD measurements. Hot applied seals were not used on low volume roads. Thus, Figure 3-9 displays the effect of traffic volume on emulsified sections MTD performance along the two years monitoring period. High traffic volume roads were expected to exhibit lower MTD values than roads with lower traffic volume.
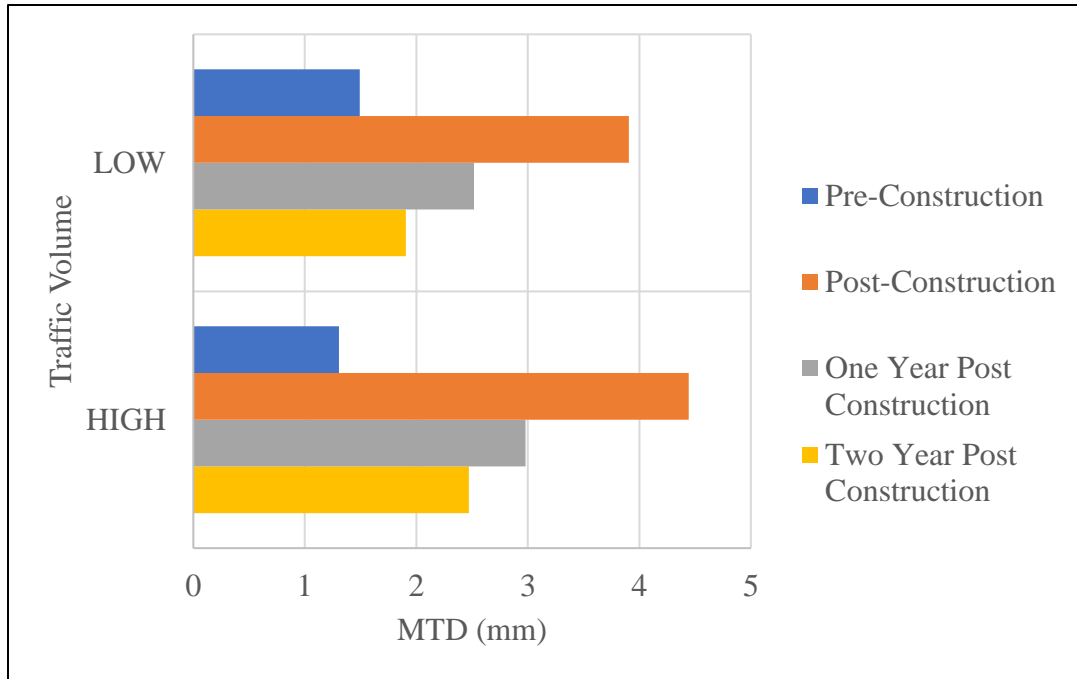
Figure 3-9 Effect of traffic volume on roadways MTD performance

Results show that traffic volume did not have a major effect on observed roadways MTD performance. Before chip seal construction, roads with lower traffic had slightly higher MTD values, which is an expected performance. However, at one weak post construction, roadways with higher traffic volume exhibited more MTD values than roadways with lower traffic volume. This shows that other factors had more contributing effect on the roadways texture properties than the sole effect of traffic. Factors might include: pre-seal condition, climate at construction, construction practices, binder and aggregate properties, binder and aggregate application rates….etc. The trend of MTD values remained the same within the two years post construction, whereby roadways with higher traffic volume exhibited higher MTD values when compared to roads with lower traffic volume.

3.3.4 Dynamic friction testing

Dynamic friction test was measured at one and two years post-construction to obtain the coefficient of friction. The DFT is placed on the pavement surface, and the internal disk rotates above the pavement. When the velocity reaches a pre-set speed, water is sprayed to the surface, and the rotating disk drops, and the sliders make contact with the pavement. Results for friction measurements were recorded across a range of speeds. Measurements were performed at 50 mph (80 kph), and results are shown in Figure 3-10 and Figure 3-11.
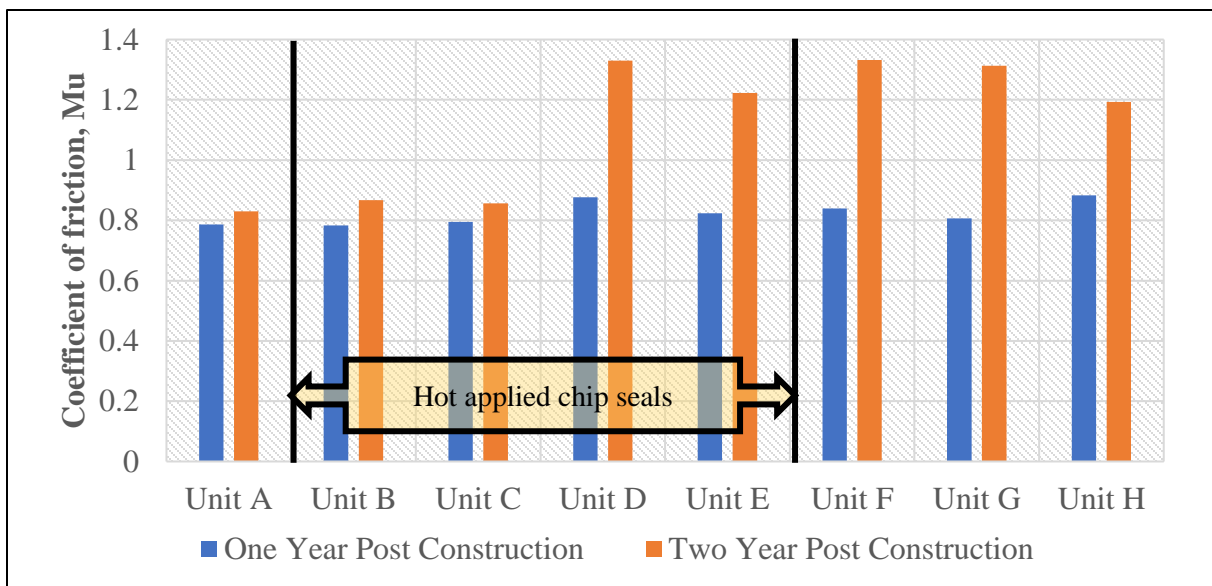
Figure 3-10 DFT comparative analysis results

According to California test C 342, a minimum COF value of 0.3 is accepted as it ensures that the sealed pavement has good skid resistance (Caltrans Division of Maintenance 2003). In general, dynamic friction test data of all units have exhibited higher values than 0.3 for both one-year and two- year post construction data. The data collected in the second year (mid-July 2016) appeared to be slightly higher than the first year (mid-July 2015) with an average variation of 20 percent.
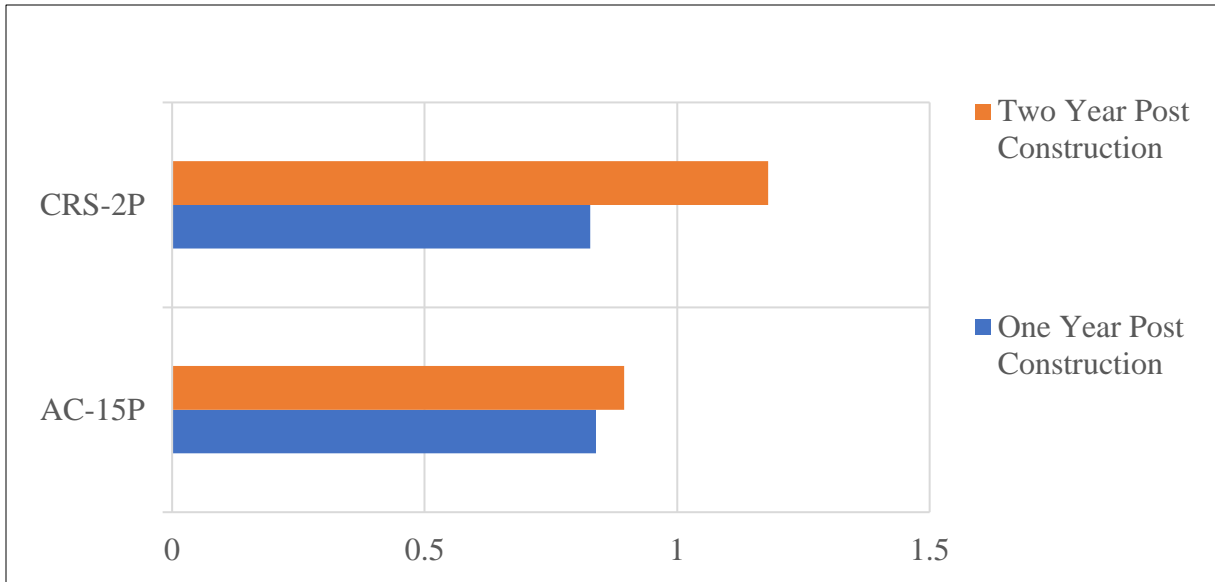
Figure 3-11 Effect of seal type on DFT results

Seasonal variation have played a role in the DFT. Upon the study of the monthly precipitation data for Oregon State from July 2014 to July 2016, it was found that the months of May and June 2016 were slightly wetter than May and June 2015. New Zealand reports higher skid values in wetter weather, since the rain removes fine dust that settles on the road leaving a grittier higher skid resistant surface. DFT field observations and recorded weather data are in agreement with the seasonal variation effect as explained by New Zealand specifications.

3.3.5 Pavement distress analysis

Chip seal studies have shown that in order to establish a sound distress performance index, field investigations should be utilized. Oregon DOT have published a distress survey manual to identify and quantify the amount and severity of observed distresses per pavement segments (Oregon Department Of Transportation 2010). The results of the survey could be used with other measured pavement characteristics to establish sound condition rating of AC pavements.

Surveys were conducted at the pre-seal condition, one-year and two years post seal construction. Severity of distresses were evaluated and addressed as being low, medium and highly severe according to distress identification manual for the long-term pavement performance (LTPP) and Oregon pavement distress survey manual (Miller and Bellinger 1989; Oregon Department Of Transportation 2010). In general, low severity cracks have a mean width less than 0.25 inches (6 mm); medium severity cracks have a mean width that lies in the range of 0.25 inches to 0.75 inches (6 mm to 19 mm), and high severity cracks have a mean width that is higher than 0.75 inches (19 mm). Severity of cracking is an important parameter to consider since it plays a major role on how quickly the cracks would be reflected throughout the pavement. Table 3-4 shows a summary of distresses severity levels identification.

Table 3-4 Summary of distress severity identification

Transverse crack severity	
Low	An unsealed crack with a mean width of < 0.25" (6 mm), or a sealed crack with sealant material in good condition and the width cannot be determined
Moderate	Any crack with a mean width > 0.25" (6 mm)and ≤ 0.75"(19 mm); or any crack with a mean width < 0.75" (19 mm) and adjacent to low severity random cracking
High	Any crack with a mean width > 0.75"(19 mm), or any crack with a mean width ≤ 0.75" (19 mm) and adjacent to moderate to high severity random cracking
Longitudinal crack severity	
Low	A crack with a mean width of ≤ 0.25" (6 mm), or a sealed crack with sealant material in good condition and a width that cannot be determined
Moderate	Any crack with a mean width > 0.25" (6 mm)and ≤ 0.75"(19 mm); or any crack with a mean width < 0.75" (19 mm) and adjacent to low severity random cracking
High	Any crack with a mean width > 0.75" (19 mm); or any crack with a mean width ≤ 0.75" (19 mm) and adjacent to moderate to high severity random cracking

Table 3-4 (continued)

Fatigue crack severity	
Low	An area of cracks with no or only a few connecting cracks. Cracks are not spalled or sealed. No pumping is evident
Moderate	An area of interconnected cracks forming a complete pattern. Cracks may be sealed. No pumping is evident
High	An area of moderately or severely spalled interconnected cracks forming a complete pattern. Pieces may move when subjected to traffic. Cracks may be sealed. Pumping may be evident
Potholes severity	
Low	< 1" (25 mm) deep(delamination of patch or seal coat)
Moderate	1" (0.25 mm) <Pothole<2" (0.5 mm) deep (remains within top lift of wearing course)
High	> 2" (0.5 mm) deep (extends beyond the top lift of wearing coarse)
Patching severity	
Low	A good quality patching with a smooth ride. The patch has , at most, low severity distress of any type including rutting or deformation < 0.25" (6 mm), and pumping is not evident
Moderate	The patch has moderate severity distress of any type or rutting or deformation from 0.25" to 0.5" (6 mm to 12 mm), Pumping maybe evident. Ride quality is good to fair
High	The patch has high severity distress of any type or rutting or deformation > 0.5" (12 mm), Pumping maybe evident. All hand patches or patched potholes are rated as high severity patches
Bleeding	
Y or N	Bleeding is present if multiple areas of 25 ft^2 (2 m^2)or larger patches are noted
Rutting	
None	0"<Rut<1/4" (6 mm)
Low	1/4"(6 mm) <Rut<1/2"(12 mm)
Moderate	1/2" (12 mm)<Rut< 3/4"(19 mm)
High	Rut >3/4" (19 mm)

Figure 3-12 shows the averaged transverse cracking lengths of observed road sections per 100 ft (30 meters), while identifying the severity of each cracking. Based upon recoded results, transverse cracking length has decreased in all roadways after the application of chip sealing. In addition, roadways that had acquired initial high transverse cracking have witnessed higher cracking compared to units with low/no-initial transverse cracking. This verifies that pavement distresses are affected by their pre-seal distress condition.
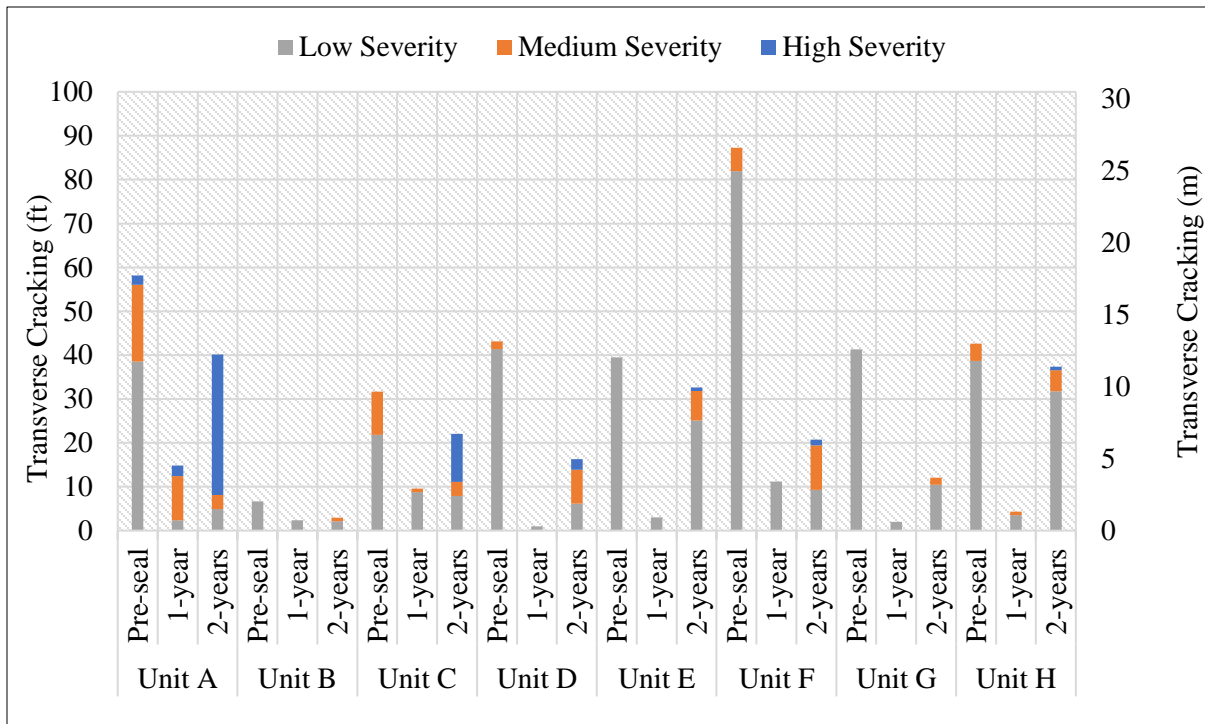
Figure 3-12 Transverse cracking by severity level

Similar findings were observed for longitudinal cracking distress, where field performance confirmed effective pavement preservation. Longitudinal cracking causes problems such as moisture infiltration, pavement roughness, and indicates presence of alligator cracking and possible structural failure. Longitudinal cracking should be recorded only if it occurs outside the wheel paths, else it should be considered low severity fatigue cracking (Oregon Department Of Transportation 2010). Figure 3-13 shows longitudinal cracking lengths of observed roadways averaged per 100 ft (30 meters) with their severity levels. Units B, D and F had high initial longitudinal cracking, but after chip sealing, the crack length has totally disappeared from unit D, and significantly reduced in units B and F. This could be tied to their underlying road conditions and recovery trends, since unit D has good underlying conditions, while units B and F had poor underlying conditions.
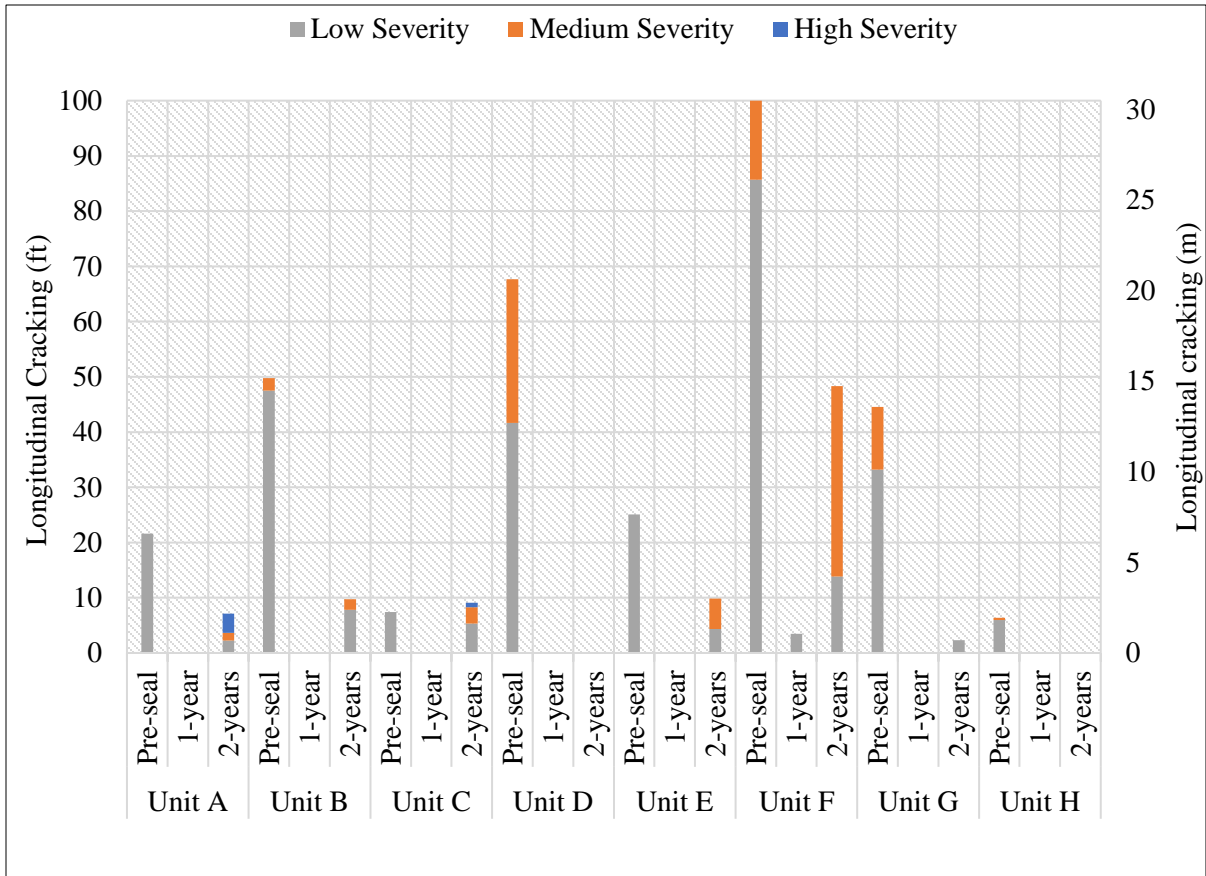
Figure 3-13 Longitudinal cracking by severity level

Table 3-5 shows the severity level of other distresses observed per roadway section over the two-years monitoring period. The table illustrates if the roadway condition has improved, stayed the same, or further deteriorated. The immediate post-sealing performance across all units showed no visual cracking or distress and thus is not displayed. Majority of observed distresses were improved across all units or remained the same. A distress presented in bold red text indicates an improvement, a distress underlined indicates deterioration, and the rest of non-highlighted/bolded distresses indicate a maintained condition.

Table 3-5 Distress results by severity Level

Distress Survey Results																								
Roadway	Unit A			Unit B			Unit C			Unit D			Unit E			Unit F			Unit G			Unit H		
Seal	Emuls.			Hot			Hot			Hot			Hot			Emuls.			Emuls.			Emuls		
Road	Fair			Poor			Poor			Good			Fair			Poor			Fair			Fair		
Time	P	1	2	P	1	2	P	1	2	P	1	2	P	1	2	P	1	2	P	1	2	P	1	2
Fatigue	L	N	N	H	N	N	L	N	N	L	N	N	L	N	N	L	N	N	L	N	N	L	N	N
Pothole	N	N	N	L	N	L	N	N	N	N	N	L	N	N	N	L	N	N	M	N	L	N	N	L
Patching	N	N	N	N	N	N	H	N	L	N	N	N	N	N	L	N	N	N	N	N	N	N	N	N
Bleeding	N	N	N	N	Y	Y	N	N	N	N	N	Y	N	N	Y	N	N	Y	N	N	N	N	N	N
Loss of aggregate	N	N	N	N	N	N	N	M	N	N	N	N	N	H	N	N	H	N	N	N	M	N	N	N
Rutting	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	L	L	L	N	N	N	N	N	N

H: High severity, M: Medium severity, L: Low severity , N: No distress observed, P: Pre-construction, 1: 1-year post construction, 2: Two-years post construction, Y: Bleeding distress is observed, Emuls: Emulsified seal, Hot: Hot applied seal.

Fatigue cracking can lead to moisture infiltration, roughness and overall roads deterioration. Fatigue cracking was observed along Unit B with high severity at the pre-seal condition. This might be attributed to its poor initial underlying road condition, which was reflected in its MTD results as well. The majority of studied roadways acquired low fatigue cracking at the pre-seal condition. Yet, chip seal application has helped reducing fatigue cracking in all roadways over the two-year performance-monitoring period. This finding is significant as fatigue cracking is usually a predecessor of potholes, which ultimately leads to failure. Thus, the ability to maintain the pavement's resistance to fatigue cracking demonstrates the success of the chip seal as an effective treatment.

A pothole is a shallow or deep hole in the pavement surface resulting from loss of pavement surfacing material. The occurrence of potholes in roadways was reduced after chip sealing application. Pre-construction surveys spotted potholes within units F, G and H. Two

years post construction surveys showed the occurrence of potholes in Units B, D and G, and an overall reduction in the severity of potholes across the rest of the units.

Patching represents areas of the original pavement surface that were removed and replaced, or if additional material is applied to the pavement surface after construction. Patching was monitored and initially appeared in Unit C. There was extensive patching done on Unit C prior to the application of the chip seal. However, Unit C required re-patching between one and two-years post construction, and still patching was observed at the two years distress survey. Based on this observation, chip seal did not preserve the patching in the distressed wheel paths, and this shows that the pre-seal condition of the roadway is linked to the performance of the seal. This observation further requires more investigation of the effectiveness of chip sealing on patching.

Bleeding and loss of aggregate cover are both chip seal related distresses that significantly affect surface-texture characteristics. The excess bituminous material on the pavement surface usually indicates bleeding. Excess bleeding usually causes reduction in skid resistance. After two years of performance monitoring, bleeding appeared in three Units, which are B, D and E. These units are all hot-applied chip seals. The binder application rate for Oregon's hot applied asphalt roadways was approximately 0.37 gal/sq.yd (1.68 l/m^2), and the binder application rate for the emulsified asphalt roadways was approximately 0.58 gal/sq.yd (2.2 l/m^2). Excess bleeding in hot applied units is mostly incorporated to the added binder from their pre-coated chips. Overall, chip sealing have proven effective in preserving pavements against bleeding.

Aggregate loss was reported across all units as a part of this study following distress identification manual for the long-term pavement performance (LTPP) report (Miller and

Bellinger 1989). Initially units C and E had some medium/high severity aggregate loss in the pre-construction investigations, but two-years after the chip seal construction, the new chip seal appears to be performing sound, and aggregate loss appeared only in one section which is unit G. Overall, chip sealing have proven effective in preserving pavements against aggregate loss

3.4 Acknowledgements

3.5 Conclusions

Chip seal construction using good quality materials and construction practices has improved studied roadways' surface micro-texture and macro-texture properties. Chip seal has reduced pavement distresses, and effectively preserved the pavements from further cracking and deterioration. Chip seal can be considered an effective pavement preservation/maintenance method. Findings showed that parameters such as aggregate properties, seal type and roadway pre-seal condition highly affect chip seal performance. Both hot applied and emulsified asphalt chip seals have successfully preserved the pavements. Both hot applied and emulsified asphalt chip seals have experienced improvements in their microtexture and macrotexture properties after chip seal application. Emulsified test sections had more improvements in their texture properties immediately after

construction in comparison to the hot applied asphalt sections. However, after two years of

roadways in-service, both sealed roadways had similar MTD values. In addition, roadways

initial condition have significantly affected chip seal performance regarding their mean

texture depth and distresses. Roadways with initial poor substrate has experienced less

frictional properties and more vulnerability to cracking.

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CHAPTER 4.   EFFECT OF SEAL TYPE AND AGING ON CHIP SEAL MACROTEXTURE PERFORMANCE: A SPLIT PLOT REPEATED MEASURES STATISTICAL ANALYSIS

Minas Guirguis[a]* and Ashley Buss[a]

Abstract

Chip seal is a pavement preservation technique that is preferred by agencies to defer future rehabilitation activities. The objective of this paper is to provide a very beneficial yet simple way to examine the effectiveness of chip seal as a pavement preservation technique, and understand the effect of factors such as seal type, age of pavement, and their interaction effect on macrotexture performance. The research provides a carefully designed experimental plan to evaluate chip seal macrotexture properties using a split plot repeated measurement (SPRM) statistical analysis. Selected emulsified and hot applied roadways in Klamath Falls were examined for their mean texture depth using sand circle testing procedure at four consequent time points: (pre-seal application, within one week of seal application, 1- year, and two-year post seal application).

Findings showed that both studied seal types (emulsified and hot applied asphalts) have provided their roadways with similar macrotexture performance; having emulsified asphalt with slightly improved texture properties, yet the difference was not found statistically significant. In contrast, environmental aging of pavements have proved to be a statistically significant factor to roadways' macro texture performance. Finally, the study emphasizes that the interaction effect of seal type and time of experimentation had the most significant effect on the resulted macro texture performance of roadways.

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4.1 Introduction

4.1.1 Background

There are generally three broad categories of pavement treatments techniques: (1) preservation, (2) rehabilitation, and (3) reconstruction (Peshkin et al. 2004). Examples of pavement preservation techniques include chip seals, fog seals, slurry seals, micro surfacing, and thin hot mix overlay. The purpose of using pavement preservation techniques is to slow down the deterioration of roads and extend pavements life. When pavement preservation techniques are applied at the right time with good workmanship, substantial cost savings can be recognized compared to rehabilitation activities (Wilde et al. 2014).

Figure 4-1 illustrates that if preservation treatments are not applied during early stages of pavements deterioration (about 40 percent), the pavements will need other costly rehabilitation/reconstruction activities.
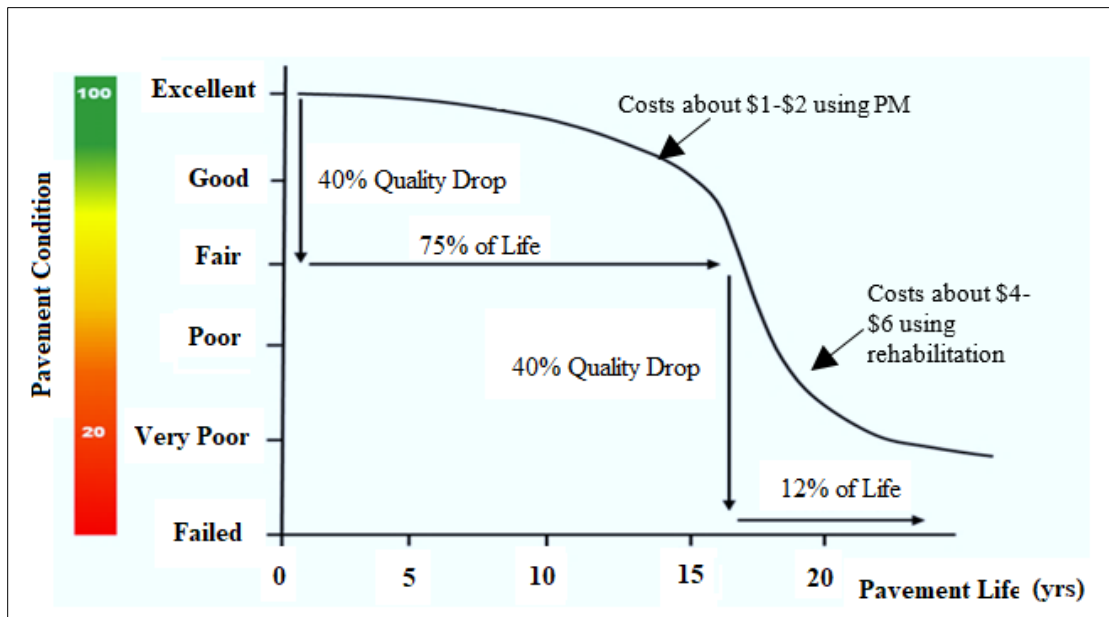
Figure 4-1 Costs of maintenance along pavement life (Peshkin et al. 2004)

One of the most commonly used preservation techniques is chip seals, which are expected to prolong the pavement life up to 7 years (Pidwerbesky et al. 2006). Chip seal is the application of asphalt binder (hot applied or emulsified), followed by the application of a single layer of aggregates - typically one stone thick, which is then rolled into the asphalt.

Chip seal application have many advantages including: texture improvements, filling and sealing cracks, providing an anti-glare surface, and increasing reflective surface under wet weather or nighttime conditions (WSDOT 2015). The primary purpose of chip seals is to protect the pavement surface from weathering factors such as: sun, water and traffic while providing satisfactory texture to the roadway surface (Ahammed et al. 2008; Asphalt Institute and AEMA 2009; Roberts and Nicholls 2008; Zaman et al. 2014).

Chip seal design and construction practices have evolved since their origin in the 1930's through research studies and site performance monitoring (Patrick 2008; Patrick and Donbavand 1996; Pidwerbesky et al. 2006). The suitability of using chip seal, as a preservation technique in a pavement network system, is based on roadway needs, traffic, available aggregate, binder types, and cost. Pavements suitable for chip sealing should be chosen after evaluating underlying pavement condition, pavement geometrics, traffic level, traffic type -urban or rural, costs, and life cycle expectations (Transit New Zealand 2005). Roadways with structural deficiencies (e.g. severe fatigue cracking, severe rutting) and roads subjected to sudden turning, accelerating or stopping movements are not good candidates.

4.1.2 Chip seal successful practices

A survey conducted by Gransberg (2005) identified common behavior between agencies who achieve excellent chip seal performance(Gransberg 2005). Many of these agencies use chip seals as a preventative maintenance (PM) tool and they expect to achieve

6-year service life. Key similarities between agencies achieving excellent chip seal performance include:

- Using formal design procedures,

- Using modified binders with polymers,

- Using pavement condition rating as a base for selecting chip seal candidates,

- Selecting roads with moderate to low distress level, and structural stability rated as good to fair,

- Using chip seal as a PM technique rather than repair/corrective technique, and

- Using quality control, quality assurance and performance monitoring programs.

4.1.3 Performance evaluation

Performance evaluation studies usually use time as a factor to assess pavements performance against environmental aging (Buss et al. 2016). Major environmental factors that degrade pavements includes moisture and temperature variations (Henning et al. 2014). Pavement exposure to traffic, aging and environmental factors significantly affects the seal's overall performance and durability. Studies usually conduct performance testing experiments at various times to the same tested sections to understand their performance while considering aging and environment exposures (Gransberg and Zaman 2005; Guirguis and Buss 2017; Zaman et al. 2014).

Chip seal pavements do not attain their texture properties with time due to mentioned factors; consequently, it is essential to understand the importance of conducting repeated performance evaluations. Short term and long term performance evaluation helps to (Federal Highway Administration 2017):

1. Determine the effect of different factors such as: loading, environment, material properties and variability in construction quality,

2. Determine the effects of specific design features on pavement performance,

3. Evaluate existing design methods,

4. Develop improved design methodologies and strategies, and

5. Establish a long-term pavement database to support future planning needs.

4.1.4 Statistical analysis

Standard statistical analysis of variance (ANOVA) of pavement performance along time do not fit the nature of repeated measurement designs, since it ignores the dependency effect of the experimental units. In other words, at each time series of testing, the response is dependent on the properties of the experimental units at hand (Buss et al. 2017). A statistical analysis is needed to isolate not only the treatment effects between different units but also the variations within experimental units of the same group that have undergone the same treatment (Littell et al. 2002). Oftentimes, researchers opt to perform a simplified analysis that generally assess one factor, as binder type, and use statistical t-test. Other studies calculate the average performance per age of the pavement (Guirguis and Buss 2017). These methods are statistically limited because they ignore the repeated measurement nature, and thus incur more errors.

This paper opts to improve the statistical methods for analyzing texture properties of chip seal performance through considerations of repeated measurements design. The paper will provide researchers with additional information about chip seal performance along time. Partial or incomplete analyses may lead to incorrect conclusions, and interactions between treatments and test conditions may go unnoticed if the entire data set is not evaluated as a whole.

4.1.5 Objectives and scope

The objective of this paper is to evaluate chip seal performance while highlighting the value of repetitive measures experimental design and analysis. Performance assessment is based upon macro-texture properties along two years testing periods. This is performed through infield sand circle testing at four different points of time conducted on various chip seal roadways located in Oregon. Two types of seals were used, which are polymer-modified hot applied asphalt (AC-15P) and polymer-modified emulsion asphalt (CRS-2P).

Time of infield testing represents short-term and long-term combined exposure factors. Time of testing includes four time points that characterize the condition of the pavements, which are: (1) pre-seal construction (before the seal application), (2) post- seal construction (within one week), (3) 1- year, and (4) 2-years post seal application. The mentioned approach would help the study to investigate the following using statistical analysis:

- The effectiveness of chip seal preservation technique through the comparison between pre-seal condition and post-seal condition,

- The effect of factors such as seal type on MTD performance,

- The effect of pavement aging and exposure to combined factors, such as environment conditions, repeated traffic loadings and asphalt aging on MTD performance,

- The Significance of the interaction effect of studied factors on chip seal MTD performance, and

- Highlight the importance of using repeated measures statistical analysis to evaluate pavement performance when repetitive testing is used.

In this study, an experimental plan is first outlined, followed by a brief discussion of field observations and performance trends. Then, a full data set will be analyzed using repeated measurements ANOVA using split plot design with the aid of SAS statistical package.

4.2 Chip Seal Performance

4.2.1 Microtexture and macrotexture surface properties

Pavement surface texture characteristics are considered critical to chip seal design. Surface texture is simply a function of two properties, which are (1) microtexture, and (2) macrotexture. Microtexture is a function of the frictional properties of the individual aggregates, while macrotexture is a function of the aggregate size, shape, and gradation. Figure 4-2 shows the difference between micro-texture and macro-texture properties.

Surface texture properties affects the amount of binder needed to hold the aggregates in place. There are a number of different methods for measuring pavements macrotexture properties. The most commonly used and accepted procedures are sand patch testing (ASTM E965) and sand circle testing (TNZ T/03) (Pierce and Kebede 2015).
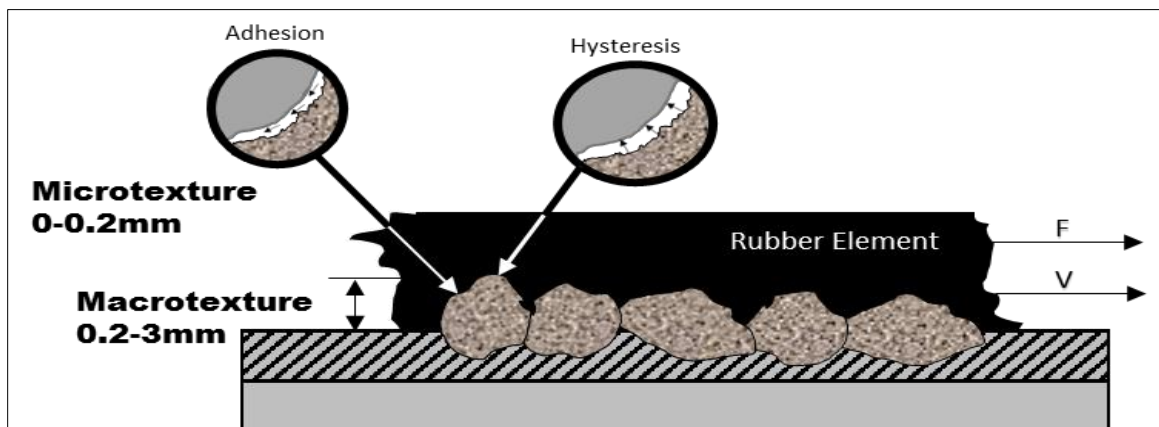
Figure 4-2 Pavement friction model (Hall et al. 2009; Pidwerbesky et al. 2006)

Both methods determine the average texture depth of a paved surface using the volume of voids. Transport New Zealand (TNZ) have further developed a performance model to calculate the texture depth at 12-months after construction. The 12-month texture depth is used as an indicator of how well the chip seal is expected to perform for the rest of its life. Final acceptance of the chip seal treatment is based on achieving the required texture depth, without any significant chip loss.

4.2.2 Effect of pavement aging and exposure factors on performance

Combined effect of environment, aging and traffic severely affect pavements performance along their serviceability to the public(Pearson 2011). Environmental factors that influence pavement performance includes: precipitation, temperature, freeze-thaw cycles, and depth to water table (Zapata et al. 2007). Moisture and temperature variations appear to be the most common factors in affecting chip seal performance. In addition to that, roadways constructed with inadequate drainage deteriorate up to three times faster than roadways prepared with proper drainage (Henning et al. 2014). In-service aging leads to oxidation and loss of flexibility of pavements. Oxidation and the associated stiffening can lead to further cracking, which in turn can lead to the deterioration of pavement's performance (Reed 2010).

Ageing of asphalt mixtures starts within the production and construction of pavements and continues throughout their service life (Yin et al. 2017). Asphalt aging under mentioned environmental conditions and repeated traffic loadings degrade the texture properties of chip seals. Therefore, a greater understanding of chip seal effectiveness and texture performance along time under possible mentioned exposures is important and necessary. Frequent pavements field monitoring and experimentation have been promoted by many studies, yet the cost of such comprehensive repeated inspections and testing of

pavements would be relatively high, and consequently many jurisdictions limit their surveys to major roads(Herold and Roberts 2005). Despite that, many States specifications (Minnesota, New York, North Carolina and Michigan) condition their chip seal projects final acceptance to their one year visual/field performance to ensure the quality of performed works(Buss et al. 2016). New Zealand specifications further provide a prediction model formula to estimate the expected life span of chip seal pavements, based on their one year texture performance results (Buss et al. 2016; Wood et al. 2006).

4.3 Experimental Plan

4.3.1 Field testing

Various chip seal roadway projects were constructed in Oregon during 2014 and 2015 construction seasons. Figure 4-3 shows a detailed map of studied roadways in Klamath Fall. The projects' roadways were constructed using either polymer-modified hot-applied asphalt, or polymer- modified emulsions. This is particularly contributing to the study, because it allows for a good comparison between the performances of hot and cold applied chip seals. Table 4-1 further provides information for each roadway including the seal type, year of construction, estimated traffic (annual average daily traffic- AADDT), and binder details.

There are generally two types of asphalt for seal coating, which are liquid asphalt and emulsified asphalt. AC-15P is a polymer modified hot applied asphalt that is designed for use as a bituminous binder for chip seals. CRS-2P is a widely used polymer modified, cationic water-based emulsified asphalts that are designed for use as a bituminous binders for chip seals. CRS- 3P is a polymer modified cationic water-based emulsified custom designed asphalt product to Portland Oregon, which provides a similar performance of a micro seal.

HFRSP2/HFE-100S is an anionic styrelf polymer modified rapid setting high float emulsion that is also used for chip with high volume roads.
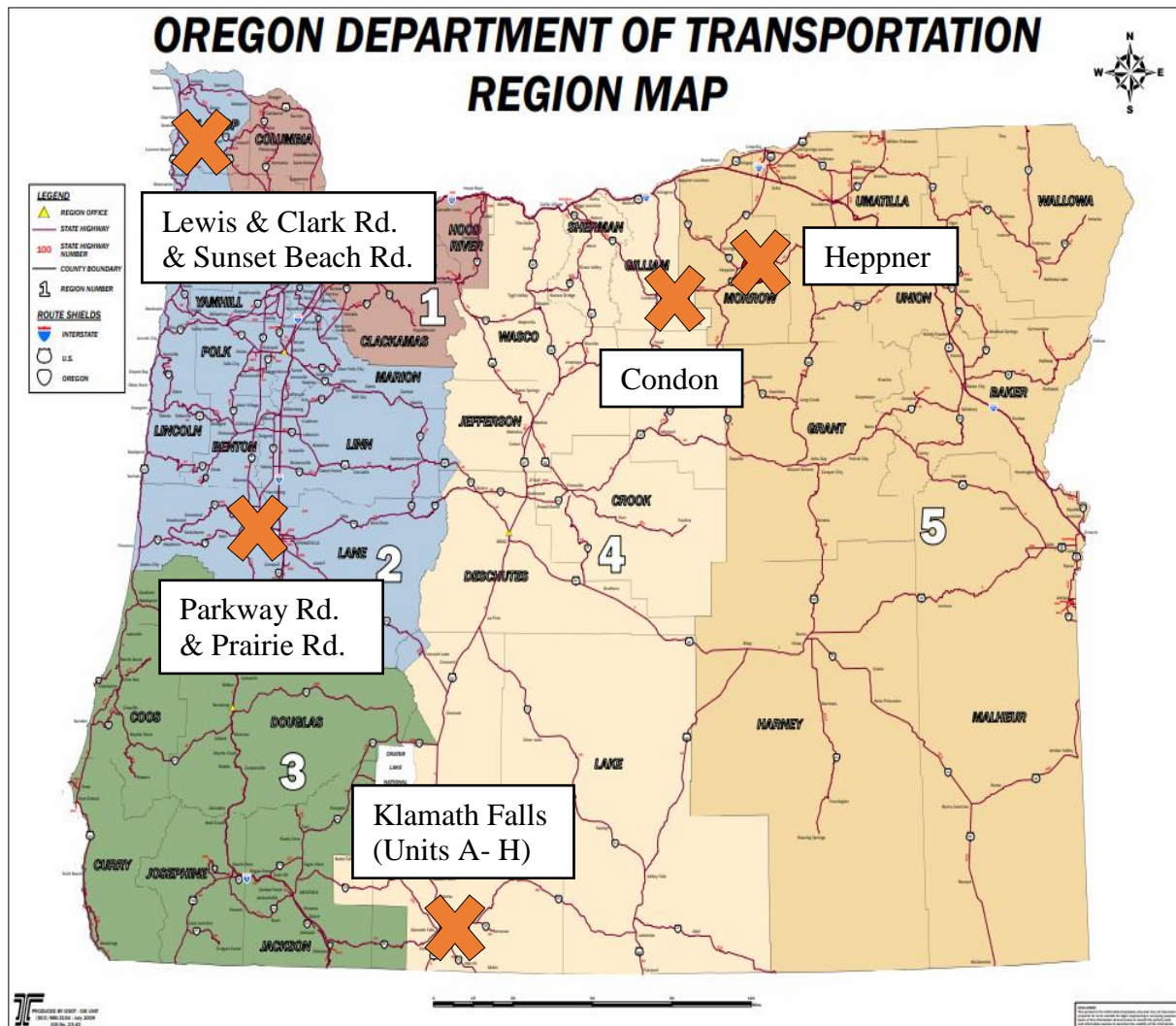
Figure 4-3 Allocation of projects on Oregon region map (ODOT Region Map,2018)

There are generally two types of asphalt for seal coating, which are liquid asphalt and emulsified asphalt. AC-15P is a polymer modified hot applied asphalt that is designed for use as a bituminous binder for chip seals. CRS-2P is a widely used polymer modified, cationic water-based emulsified asphalts that are designed for use as a bituminous binders for chip seals. CRS- 3P is a polymer modified cationic water-based emulsified custom designed asphalt product to Portland Oregon, which provides a similar performance of a micro seal.

HFRSP2/HFE-100S is an anionic styrelf polymer modified rapid setting high float emulsion that is also used for chip with high volume roads.

Table 4-1 Summary of studied roadways

Test section	Roadway	Seal Type	Year of Constr.	AADT	Seal Details
1	Prairie Road	Hot applied Asphalt Surface Treatment	2014	4000-5200	AC-15P
2	Parkway	Hot applied Asphalt Surface Treatment	2014	2800	AC-15P
3	Lewis & Clark Rd.	Emulsified Asphalt Surface Treatment	2015	465	CRS-3P
4	Sunset Beach	Emulsified Asphalt Surface Treatment	2015	1521	CRS-3P
5	Condon	Emulsified Asphalt Surface Treatment	2015	470	HFE-100-S or HFRS-2P
6	Heppner	Emulsified Asphalt Surface Treatment	2015	1000	HFRSP2/HFE100 S
7	Klamath Unit A	Emulsified Asphalt Surface Treatment	2014	460	CRS-2P
8	Klamath Unit B	Hot applied Asphalt Surface Treatment	2014	2300	AC-15P
9	Klamath Unit C	Hot applied Asphalt Surface Treatment	2014	2900	AC-15P
10	Klamath Unit D	Hot applied Asphalt Surface Treatment	2014	1280	AC-15P
11	Klamath Unit E	Hot applied Asphalt Surface Treatment	2014	1345	AC-15P
12	Klamath Unit F	Emulsified Asphalt Surface Treatment	2014	2650	CRS-2P
13	Klamath Unit G	Emulsified Asphalt Surface Treatment	2014	670	CRS-2P
14	Klamath Unit H	Emulsified Asphalt Surface Treatment	2014	690	CRS-2P

The study followed New Zealand developed sand circle test (TNZ T/03) for macro texture infield testing. Prior to conducting the test, the surface was cleaned from any dust or debris, and then silica sand was spread to form the circles in level with the pavement surface. Diameter of the sand circles was measured and the MTD was calculated accordingly.

4.3.2 Statistical experimental plan

An experimental plan was further developed to evaluate the performance of chip seals and determine which factors most affect their roadways macrotexture performance. The process is summarized in four stages described below.

Stage 1: Identifying the experimental units

Experimental units represent the subjects to which treatments were randomly assigned. Units (A-E) located in Klamath Falls were chosen for the statistical analysis. They were chosen for un-biased balanced statistical analysis, since they are constructed within the same locality, at the same construction season of 2014, and by the same contractor. The analysis is balanced, since four of which were constructed using hot-applied asphalt, and the other four were constructed using emulsified asphalt.

Stage 2: Conceptualizing the treatment design (Factors-Structure)

The treatment design involves having two factors, each with different levels, to represent the full treatment conditions. In this study, a (2*4) factorial design with 8 treatment combination conditions are identified. Seal Type consists of two levels (hot applied seal and emulsified seal, and will be called whole plot levels. Time of experimentation consists of four levels (dates of experimentation including: June 2014, July 2014, July 2015 and July 2016), and will be called subplot levels.

Stage 3: Conducting field experimentation and identifying response variable

shows the lay out of the field experimentation per roadway. Each roadway was divided into three test sections, each of 500-foot length for experimentation. Sand circle test is conducted four times on each subsection in accordance with (TNZ T/3: 1981). Testing was repeated at four different time points on each roadway subsections making 480 data point (8 roadways*3 subsections* 5 measurements * 4 timings) for the statistical texture analysis. The response variable is the mean texture depth measured using the sand circle test.

Such statistical analysis of the response variable (MTD) would leads us to understand two behavior parameters related to performances of chip seal. The first parameter is how roadways texture properties change from pre-seal condition to post-seal condition. The second parameter investigated is how texture performance of hot applied asphalt compares to texture performance of emulsified asphalts, while considering short-term and long-term aging, exposure to climate and traffic loadings. The advanced statistical analysis, introduced in this paper, will provide a clear understanding of how all these factors interact together.
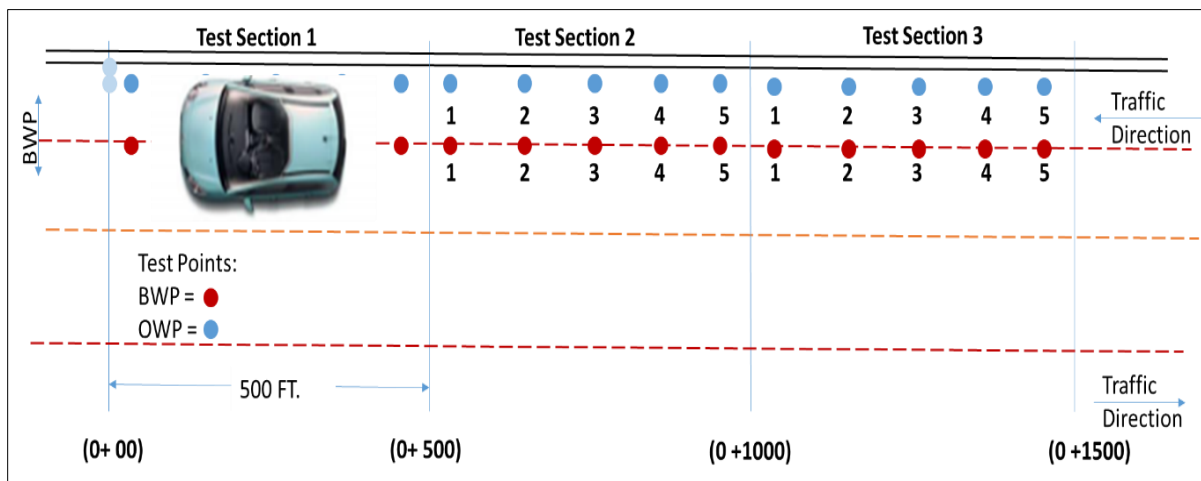
Figure 4-4 Schematic plan of field experimentation

Repeated measures ANOVA analysis

Analysis of variance (ANOVA) is a statistical method that has been used in most studies to test differences between two or more means of different group(s). It is called analysis of variance as it tests means by analyzing their variances (Akritas 2015). The normal-model based ANOVA analysis assumes independence, normality and homogeneity of the variances of the subjects. The null hypothesis states that the means are equal, while the alternative hypothesis states that the related group's population means are not equal or at least one mean is different to other means.

Four basic assumptions should be true when using ANOVA analysis, which are (Akritas 2015):

1. They are normally distributed,

2. The errors are independent,

3. The expected values of the errors are zero, and

4. The variances of all errors are equal to each other.

In this experimental design, the errors of the experimental units (roadways) are not independent, because measurements are taken from the same location at different points of time. For this reason, it is important to isolate the error relevant to each roadway unit, before ANOVA analysis is performed. Consequently, the study use repeated measures ANOVA instead of simple ANOVA analysis. Repeated measures ANOVA are used when measurements are made on the same experimental unit at successive points of time (Cobb 1998). It provides both an understanding of possible changes in a group's performance and the specimen-to-specimen variations.

In this study, repeated measures ANOVA would study: (1) the differences in mean values due to seal type, (2) the changes in mean values over the studied four time points, and

(3) the changes in mean values due to the interaction between both factors. The ANOVA analysis would provide a statistical test of whether or not the means of several groups are equal for statistical significance.

When dealing with pavement performance, there is always ambiguous/un-identified factors that must be considered in the design and analysis. The variability within the group is important when performing statistics. The variability of the pavement response at different points of testing must also be accounted for. Understanding such types of variability and isolating the treatment effect using two error terms is where the SPRM analysis becomes very beneficial

Repeated measures ANOVA divide the error term, which results in reducing its size and acquiring a higher power of the test. In repeated measures ANOVA, the independent studied variable has categories that are called levels, where measurements are repeated. In
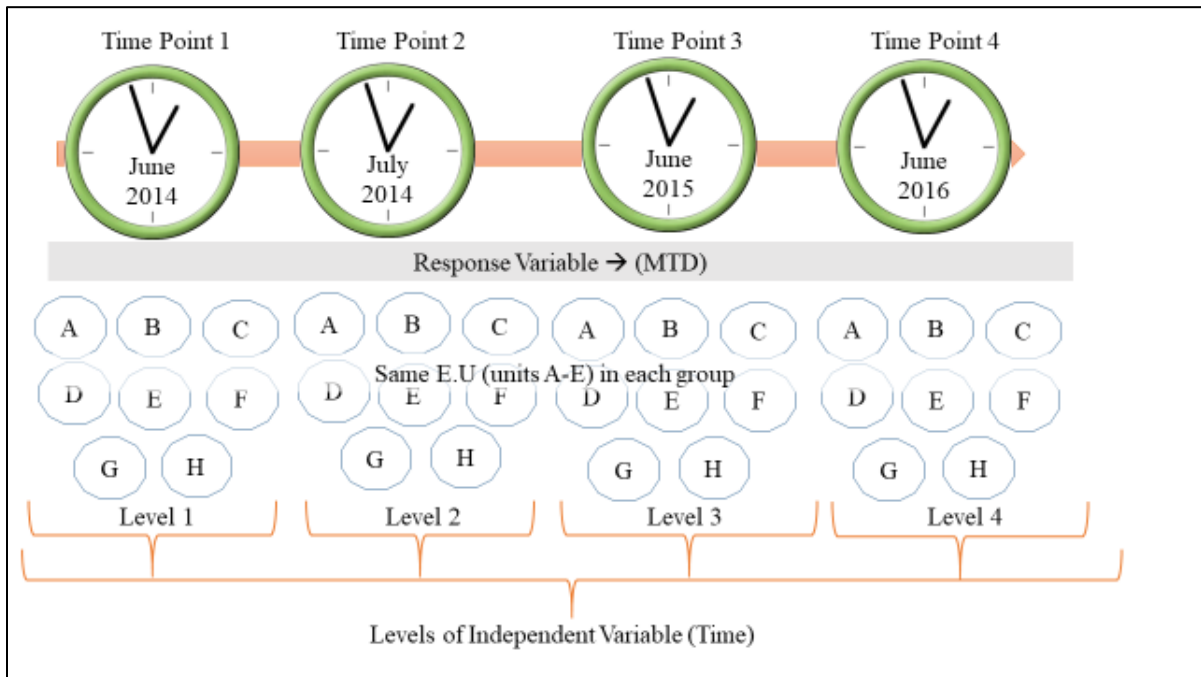
this study, each level is a specific time point at which MTD is reported. Hence, there are four

Figure 4-5 Schematic design of repeated measures study

levels of the independent variable "time". Figure 4-5 shows a schematic plot of the time-course repeated measures design.

Two important statistical parameters that measure variation within and between the experimental units are the mean square error (MSE) and the mean square treatment (MST). The ratio of the two values (MST/MSE) is the F-statistic. The F-statistic is compared with the appropriate F-distribution, and a p-value is obtained. P-value determines statistically if there is any significant differences between the means at the chosen alpha level (0.05).

Split-plot repeated measures (SPRM)

The experimental plan is designed to isolate each factor of interest, as well as different sources of error, by using a SPRM design. SPRM experimental design isolates the errors taken from the same experimental unit to isolate the variability between experimental units treated the same. Split-plot experiments divides the factors of interest into whole plots and split plots factors. In this design, the two main whole plot and split plot factors of interest are seal type and time of testing, respectively. Whole plot factor levels are hot applied seals and emulsified seals. Split plot factor levels are each specific time of testing.

Figure 4-6 represents a diagram of the statistical design categorizing the experimental factors. Eight whole plot experimental units represents Oregon's roadways. The split-plot factors includes the points of time at which each whole plot experimental units is tested. Levels of each factor are as follows: seal type (two levels), time of testing (four levels). A replicate of 15 testing points are repeated per testing time. The experimental units' response variable is mean texture depth measured in the field using sand circle test.

Whole Plot E.U	Whole Plot Factors		Sub Plot Factors (Time)	Response Variable
Klamath unit B Klamath unit C Klamath unit D Klamath unit E	Hot Applied Seal	15 Test Section Per E.U	• Pre-chip seal • (June 2014) • Post-chip seal • (July 2014)	Mean Texture Depth
Klamath unit A Klamath unit F Klamath unit G Klamath unit H	Emulsified Seal		• One-year-post chip seal • (July 2015) • Two-year-post chip seal (July 2016)	

Figure 4-6 SPRM experimental design

4.4 Results and Analysis

4.4.1 Simple analysis

Figure 4-7 shows Oregon roadways' MTD performance evaluation results. Each test section was investigated before the application of the chip seal, post the application of chip seal (within a week), at one-year and two-years post construction. At close inspection, one could notice that the mean texture depth of all roadways at the pre-construction condition was lower than the other conditions. New Zealand specifications set a minimum accepted value for MTD measurements of 0.9 mm. Roadways such as units B, C and F have failed such specification at the pre-construction state.
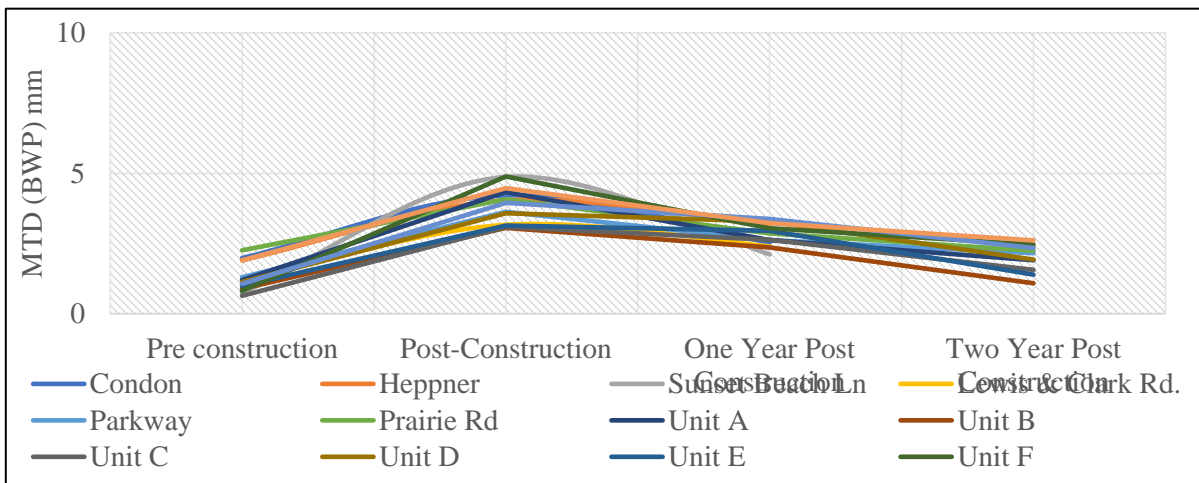
Figure 4-7 Macrotexture field results

Major advancements in texture measurements were found at the post construction measurements when compared to the pre-seal condition. Figure 4-8 compares the performance of emulsified and hot applied seal sections along their two years post construction periods. Emulsified sections had higher texture properties than hot applied sections at their one-year post construction performance. Yet, the slope is not as steep as it is at two years post seal construction. At two years post seal construction, emulsified sections had much higher texture measurements than hot applied sections. As an overall performance, after the application of chip seal, both seal types sections have attained satisfactory texture measurements when compared to New Zealand chip seal specification of a minimum accepted value of 0.9 mm.
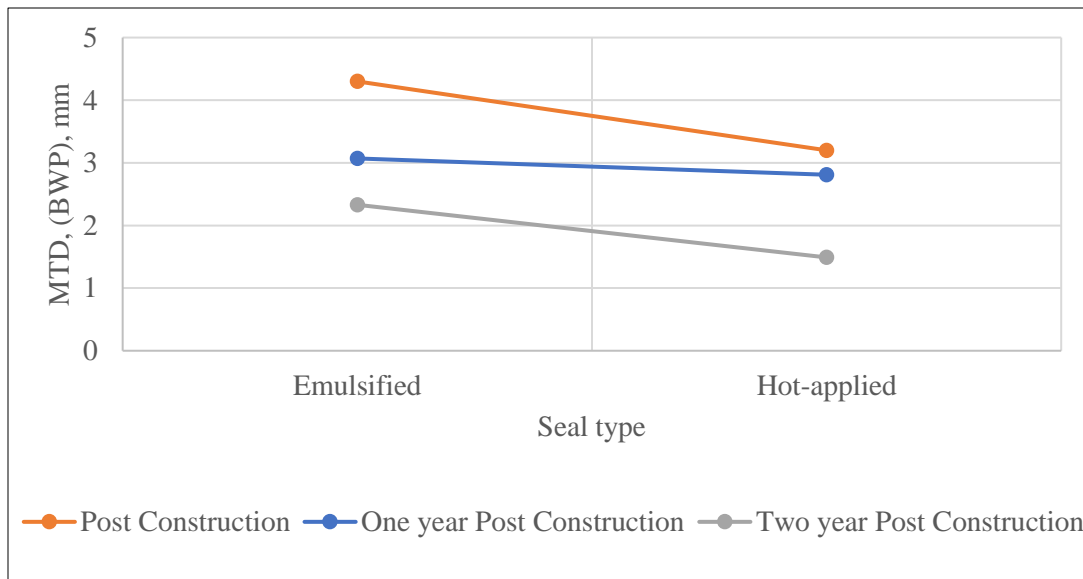
Figure 4-8 Effect of seal type on post construction performance

4.4.2 SPRM analysis

Full statistical analysis is necessary to provide a complete understanding of the roadways texture performance along time. SPRM is used due to the repetitive nature of the experimentation. MTD testing is repeated on the same experimental units (roadways' test

sections) multiple times, and the analysis needs to account for taking multiple readings from the same experimental unit. SPRM analysis accounts for the random error, which assumes that the variations within the roadways test sections are treated the same. This variation could result from differences in initial road condition, application rates, materials differences….,etc. The error term of the repeated measures within the experiment is a result of the interaction between seal type, time of testing and experimental units.

The whole plot factor in this experiment is seal type: hot applied versus emulsified asphalt. The analysis of data from a SPRM experiment can be represented as having two separate parts: the whole plot analysis part and the subplot analysis part. In the whole plot analysis, the effects of the whole plot factor (seal type) on the MTD measurements is examined. The whole plot experimental units are the roadways test sections. In the subplot analysis, the effect of subplot factor (time of experimentation) on the MTD measurements for each experimental unit is examined. In the SPRM analysis, variation in MTD measurements are due to the treatment combination conditions of seal type and time point effect. Seal type is nested to the experimental units, because the effect of the two seal types on the experimental units' MTD measurements is of interest.

The estimated effects of levels of a given factor are calculated as the difference between the average MTD for each level and the overall average MTD. A sum of squares for "seal type" is calculated from the weighted sum of squares of the estimated effects. The weights are determined by calculating the number of experimental units of each seal type. The "seal type" sum of squares quantifies how much variation in MTD can be attributed to the seal type. The statistical significance of this variation is determined by comparing the sum of squares of "seal type" to how much variation is present in the MTD values, due to the

possible sources of differences between the experimental units that are treated the same
(treated with same seal type). This measure of possible variation is the mean square of the
experimental units, "experimental units [seal type]".

The F-statistics represents the ratio of the mean square of each factor to the mean
square of "experimental units [seal type]", and is used to determine the probability (P-value).
If the P-value is smaller than a chosen significance level (usually 0.05), then the factor of
interest is said to have a statistically significant effect at that level of significance. In a
similar way, the interaction effect of two factors on the response variable can be quantified
by the sum of squares of the two factors looked at together, (e.g., seal type* time). The F-
statistic and the P-value are calculated from the sum of squares of the interaction and the
mean square of the "experimental units [seal type]".

Note that the whole plot analysis is not influenced by variations in MTD due to time
factor, because the average values for each roadway unit is used. The whole plot analysis is
followed by the subplot analysis where the effects of time (representing short term and long-
term exposure factors) are considered.

The interaction effect between whole plot and subplot factor are addressed in the
subplot analysis. MSE is used as the denominator for the F-statistics to establish the
statistical significance for the subplot analysis. This MSE quantifies the residual error, which
is the random variation that has not been accounted for by the factors and interactions.
Developed code to conduct ANOVA using split plot design with the aid of SAS statistical
package is shown in APPENDIX A. The summary of the model fit is shown in Table 4-2. R^2
is the proportion of response variability (MTD) as explained by the model. If the model fits
the data perfectly, R^2 would reach 1, yet it can also be deceptive as it increases when the

model parameters increase. Adjusted R² is a modification of R² that adjusts automatically for the number of parameters considered in the model. It only increases when the terms added to the model improve the fit more than would be expected by chance. In this study, having an R^2 and adjusted R^2 of 0.86 infers that the model provides good fit to the data. Table 4-2 Summary of model fit (SPRM)

Table 4-2 Summary of model fit (SPRM)

R²	0.87
Adjusted R²	0.87
Root Mean Square Error	0.42
Mean of Response	2.43
Observations	480

ANOVA table for fixed effect tests is shown in Table 4-3. The degrees of freedom (DF), sum of squares (SS), F-ratio and P-values for each factor and their interaction are presented. Comparing to a P-value of 0.05, the ANOVA analysis did not find enough evidence to indicate statistical significance of used seal type on the MTD performance. Yet, the analysis confirmed that the effect of pavement aging, exposure to traffic, and environmental factors (time of testing) was statistically significant. In addition, the interaction between both factors (Seal type*Time of Testing) was found very significant on the MTD performance

Table 4-3 Fixed Effects test

Source	D.F	SS	F- Ratio	P-value
Seal Type	1	52.05	3.07	0.11
Time of Testing	3	539.86	938	<0.0001*
Seal Type * Time of Testing	3	17.73	32.1	<0.0001*

Multiple comparison tests and least squares (LS) means plots were further used to interpret the statistical differences and better understand the factors interactions effect.

4.4.3 Multiple comparisons testing

Least square means (LS Means) plots provide a very effective tool to compare between group's responses with respect to the factors studied and their interaction effect. LS Means are estimated from a linear model in contrast to the simple average of values that was used in the simple analysis of results. Least squares means are adjusted for other terms in the model (like covariates), and are less sensitive to missing data. Theoretically, they are better estimates of the true population means than using the arithmetic averages (Akritas 2015).

Figure 4-9 shows the effect of seal type (emulsified and hot applied seals) on the MTD performance. Emulsified chip seal roadways exhibited higher MTD than hot applied chip seal roadways, yet the difference in MTD values is statistically insignificant. Both seal types have statistically resulted in having similar MTD performance. The plot shows the LSM and their corresponding 95 % confidence interval. Note that overlapping confidence intervals do not necessarily indicate statistical significance.
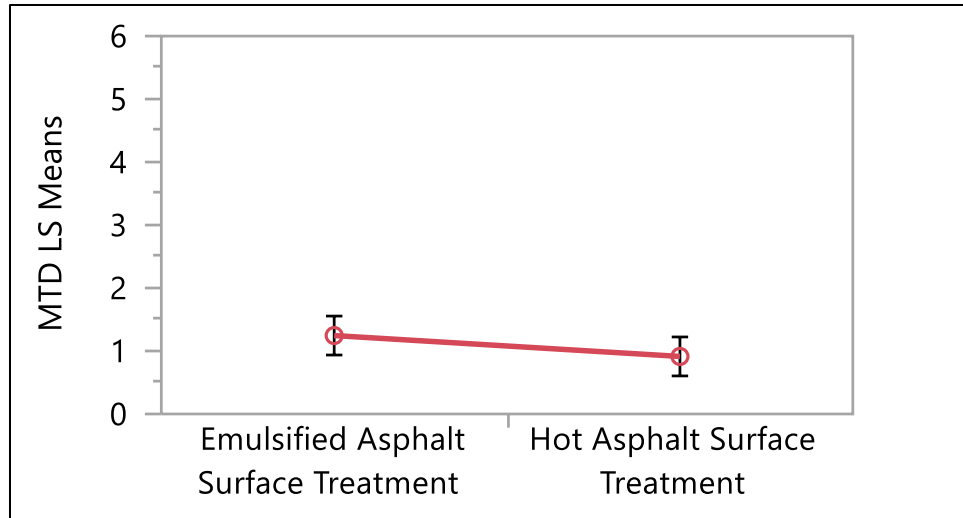
Figure 4-9 LS means plot for whole plot factor (seal type)

Figure 4-10 shows the MTD results along the four time points of pavement testing. The plot shows improvements of MTD measurements between the pre-seal condition and the rest of post seal conditions. The plot also shows that there is a reduction in MTD values from the post-seal condition up to the two years post-seal condition. This is expected since the roadways are exposed to aging, traffic loading, weather, freezing and thawing cycles, distresses…..etc . Significance of time effect demonstrates how important it is to conduct chip seal performance testing, and ensure that the reduction in texture is still in acceptable limits.

 shows the interaction effect of investigated factors between the whole-plot levels and sub-plots levels, that is: seal type and time of testing. The analysis was able to capture differences between seal types performance along time. This was largely due to the fact that the variability of the individual experimental units was isolated reducing the error term, thus making it possible to detect variations between chip seal types.

Figure 4-10 LS means plots for sub-plot factor (time of testing)

Figure 4-11 LS Means Plots for Interaction effect

A two-way interaction exists between seal type and different times of testing. The interaction investigation can be divided into two parts: (1) evaluating the introduction of both seal types to the roadways and (2) evaluating the performance of both seal types with regard

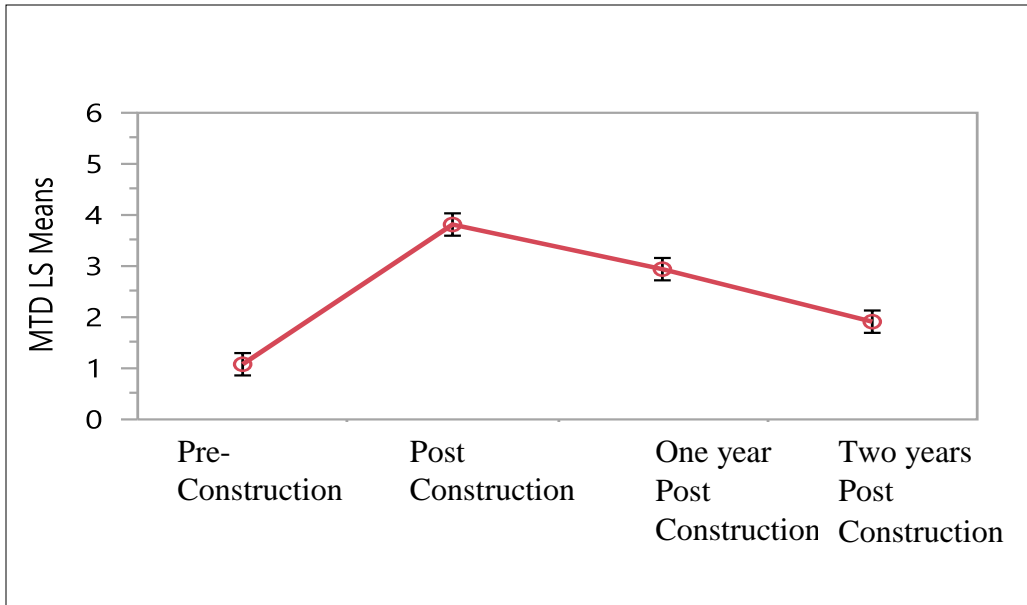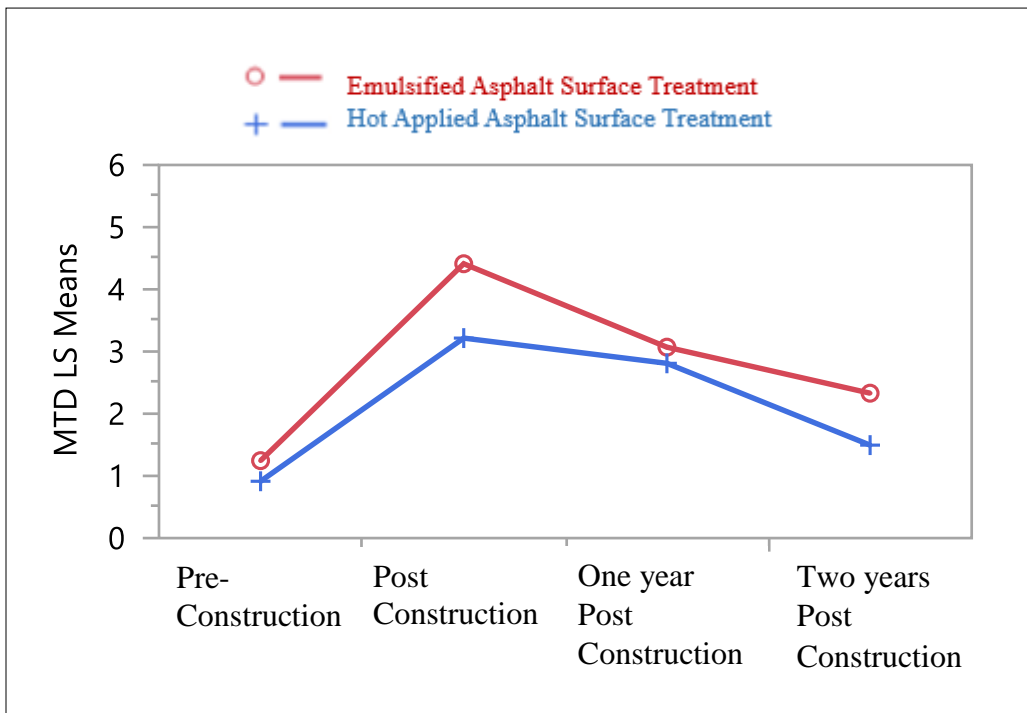to aging, traffic loading and weathering conditions. The LS Means plot indicates that chip seal introduction using both emulsified and hot applied asphalt had statistical texture improvement when compared to their pre-seal condition. Both seal types had satisfactory MTD measurements at one year and two years post construction, when compared to specifications. Emulsified asphalt seals had exhibited higher MTD values when compared to hot applied seals at the four times of testing. However, at one-year post construction, both seals had close MTD performance. At two years post construction, hot applied chip seal sections had a higher rate of texture loss, leaving emulsified sections with higher texture properties.

4.5 Conclusions

Simple analysis using subsets of mean texture depth data provided some information about differences in chip seal performance. However, using such subsets could not provide an overall picture of all data and full influence of the interaction between factors, which are seal types and pavements environmental aging, which was only possible by means of SPRM analysis. Implementing a SPRM analysis using infield MTD measurements provided improved data interpretation, and helped in clarifying possible behavior variations in chip seals performance.

Findings verifies that using chip seal, applied with both seal types (hot applied and emulsified), have led to a statistically major texture improvement effect on MTD measurements, which proves that chip seals can provide successful pavement preservation technique using both types of seals. Results show that time of testing (i.e. age of pavements) had a statistically significant effect on MTD behavior of observed roadways. A significant effect was further found between the interaction of both factors seal type and age of pavements on the MTD performance.

Along the two years of pavement experimentation, emulsified asphalt chip seal roadways have acquired higher MTD values when compared to hot applied asphalt chip seal roadways. Although at one-year post construction both seals had close MTD performance, at two- years post construction hot applied roadways experienced a higher rate of texture loss, resulting in having the emulsified asphalt chip seals with better MTD measurements.

Asphalt industry relies on performance testing, thus a systematic analysis that depend on studying different factors that affect chip seal performance is always beneficial. Using a SPRM statistical analysis, as demonstrated in this paper, to study such factors along others would provide a very beneficial way to investigate different intertwined effects of all possible complex experimental parameters that could affect pavements performance.

4.6 Acknowledgements

4.7 References

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CHAPTER 5.   PROMOTING THE USE OF CHIPSEAL RATIONAL DESIGN APPROACHES

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Abstract

Chip seal research advocates for performing rational design computations prior to construction to determine the initial chip and binder application rates. This paper is a result of a study that investigated ways to improve chip seal design specifications in Oregon. The research aims at encouraging agencies and contractors to adopt rational chip seal design methodologies, through understanding the parameters considered, and showing straightforward procedures to follow such approaches. The study uses different projects located in the US to compare between infield application rates (based upon agency's previous experience) and rationally estimated rates. Rational design methodologies require the conduction of laboratory and field-testing prior to computing any chip seal quantities. They require involved parties to: (1) understand the properties of chip seal materials (aggregate and binder), (2) identify pre-seal road condition, and (3) use said information in the design process. Findings shows that projects constructed using infield application rates close to rational estimated rates had better embedment and estimated life span when compared to the rest of projects that had excessive aggregate amounts and less binder content.

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5.1 Introduction

5.1.1 Background

The very early practitioners of chip seal surface treatments have used a purely empirical approaches to attain their designs (Gransberg and Zaman 2005). Chip Seal design mainly involves the calculation of correct amounts of a bituminous binder and aggregates. Two major design parameters are the type and amounts of required binder and aggregate.

In the mid-nineties agencies reported inconsistencies in their chip seals performance and repeated instances of failures incidents. As a result, there was a decline in the use of chip seals for various years (Wood and Olson 1989). Minnesota DOT worked in partnership with the Minnesota local road research board to address identified chip-seal related problems to modify their chip seal program. Minnesota chip seal study had a strong consensus on the importance of adopting performance based "rational" design, which require pre-sealing laboratory and field-testing to reasonably estimate application rates. Testing mainly address aggregate properties and in field pavements condition. Minnesota study revitalized chip seal design and practices, and agencies who followed the program have reported that their projects performed better than was expected (Wood and Olson 1989).

NCHRP Synthesis 342 reported that many US public road agencies remain treating chip seal as a commodity rather than an engineered preservation tool, as they still ignore using rational design approaches, and depend on their experience and empirical methods (Gransberg and James 2005). The following points summarize important considerations to ensure chip seal application success (Wood and Olson 1989): (1) follow a rational design procedure, (2) use chip seal appropriate materials, and (3) apply the proper amount of asphalt binder and chips.

Hanson presented the first recorded effort to produce a rational design procedure for chip seal (Hanson 1934). Hanson reported that an optimum design would be reached when chips are 80 percent embedded to the binder. Hanson accordingly introduced a new concept which is aggregates average least dimension (ALD), and Figure 5-1 illustrates the concept. ALD is the reduction of the median particle size of each aggregate after accounting for traffic loading that forces the aggregate particles to lie on their flattest side.
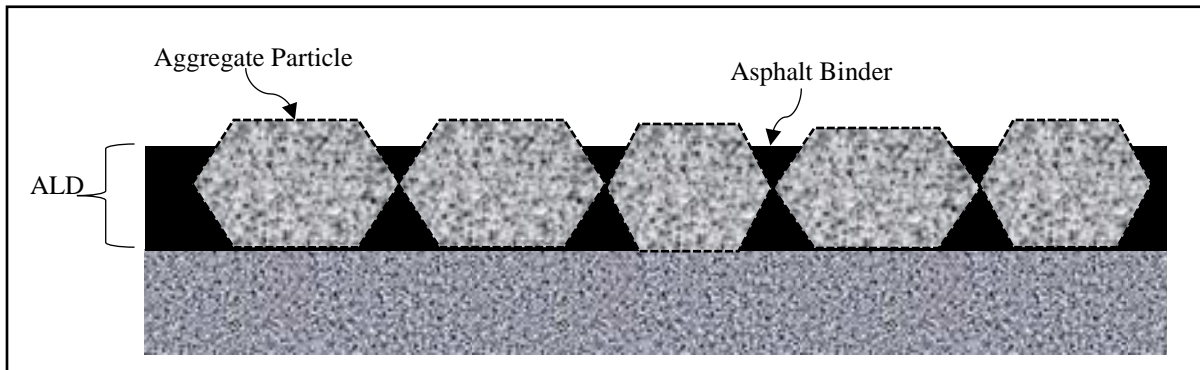
Figure 5-1 ALD of chip seal layout

5.1.2 McLeod design

Another approach that developed after Hanson and considered more factors and allowances for aggregate properties and site conditions is McLeod approach. The chip seal design summarizes the design process into three main components, which are binder application rate, aggregate application rate, and correction factors. Binder application rate depends on aggregates properties, such as: gradation, absorption, shape, traffic volume, pavement condition, and binder residual asphalt content. McLeod expressed this approach using a set of simple formulas, shown in Equations (5 – 1) to Equations (5 - 4) (McLeod et al. 1969; Wood et al. 2006). Table 5-1 is developed to show McLeod suggested correction factors to correlate environmental conditions to performance.

$$ALD = \frac{M}{1.139285 + (0.011506)*FI} \qquad \text{Equation 5-1}$$

$$V = 1 - W/(1000 * G) \qquad \text{Equation 5-2}$$

$$R_{ML} = [0.4\,(ALD) \times T \times V + S + A + P]\,/\,R) \qquad \text{Equation 5-3}$$

$$A_{ML} = (1 - 0.4V) \times ALD \times G \times E \qquad \text{Equation 5-4}$$

where, ALD = Average least dimension of the aggregates (mm),

M= median particle size (mm),

FI = flakiness Index,

V = voids in loose aggregate,

W = loose unit weight,

G =bulk specific gravity,

R_{ML} =McLeod binder application rate (liter/m^2),

T= traffic correction factor,

S= surface condition correction factor (l/m^2),

A= aggregate absorption (l/m^2) - in accordance with CTM 303,

P= surface hardness correction factor (l/m^2),

A_{ML} = aggregate application rate (kg/m^2),

E = Whip- off factor (%), and

R = residual value. [Residual value for emulsified binders vary from 0.6 to 0.7, and

residual value for hot applied binders is 1(Shuler 2011)].

Each factor considered in above equations accounts for a certain field condition.

Traffic factor (T) accounts for traffic volumes and their effect on aggregates embedment.

Whip off factor (E) considers the effect of traffic during curing on whipping some aggregate

to the sides of the roadway. Surface condition factor (S) accounts for pavement initial surface

condition. Surface hardness factor (P) considers the combined effect of pavement

hardness/softness and traffic volume.

Table 5-1 McLeod factors (McLeod et al. 1969; Wood et al. 2006)

Traffic Factor (T)						
Traffic factor, based upon Traffic volume	Vehicles/ Day (AADT)	0-100	101-500	501-1000	1001-2000	>2000
	T	0.85	0.75	0.7	0.65	0.6
Whip - off Factor (E)						
Whip off Factor, based upon road type/function	Road Type	Rural & Residential	High Volume Roads		State High Ways	
	E	1.05	1.1		1.15	
Surface Condition Factor (S)						
Surface condition factor, based upon road surface state (l/m^2)	Existing Pavement	Black, flushed asphalt	Smooth non-porous/ smooth	Slightly porous, oxidized /matte	Slightly pocked, porous, oxidized	Badly pocked, porous, oxidized
	S	-0.31	0	0.14	0.27	0.4
Surface Hardness Factor (P)						
Surface Hardness Factor, based upon traffic volume and ball penetrometer test (l/m^2)	Traffic Volume/Lane (AADT)	150-300	300-625	625-1250	1250-2500	>2500
	P -Hard (ball value 1-2)	0	0	0	-0.1	-0.21
	P-Medium (ball value 3-4)	0	0	-0.1	-0.2	-0.3
	P-Soft (ball value 5-8)	-0.1	-0.1	-0.2	-0.3	-0.4

5.1.3 New Zealand design

Many effort and studies have been conducted in New Zealand and Australia regarding

chip seal design and construction practices. New Zealand method introduces infield testing to

consider allowances for pavement surface texture properties (i.e. macrotexture). Considering

texture parameters would reduce possible uncertainty, and leads to minimal field

adjustments. New Zealand approach uses a set of Equations (5-5 to 5-8) to reach the rational

estimates (Transit New Zealand 2005).

$$e = 0.21 \text{ MTD} - 0.05 \qquad\qquad \text{Equation 5-5}$$

$$\text{MTD} = 57300 / (D)^2 \qquad\qquad \text{Equation 5-6}$$

$$R_{NZ} = (0.138 \text{ ALD} + e)T_f \qquad\qquad \text{Equation 5-7}$$

$$A_{NZ}\,(\text{m}^2/\text{m}^3) = 750 / \text{ALD} \qquad\qquad \text{Equation 5-8}$$

where, e = surface texture correction factor $(1/\text{m}^2)$,

MTD = mean texture depth (mm),

D = diameter (mm),

R_{NZ} = binder application rate (liter/m^2),

ALD = Average least dimension of (mm),

e = surface texture correction factor (/m2),

T_f = adjustment factor for traffic, and

A_{NZ} = aggregate application rate (m^2/m^3)

5.1.4 Objectives and scope

Many US public road agencies and contractors still ignore using rational chip seal design approaches and depend on their previous experience and empirical methods. Consequently, inconsistencies in chip seals performance and some instances of early failures have been reported. The purpose of this study is to demonstrate the importance of using rational chip seal design approaches to ensure performance as well as save unnecessary costs of using excess materials or redoing works.

The research uses actual projects' data to conduct a comparative analysis between infield application rates and rationally suggested rates. The analysis is undertaken to determine if projects constructed with close application rates to rationally estimated rates would perform better in terms of embedment and overall expected life span.

The following methodology is established using case studies that were proctored for one-year to:

1. Evaluate the properties of used aggregates, and identify projects'pre-seal texture conditions through laboratory and field-testing,

2. Use said information to estimate rational design quantities using McLeod and New Zealand methodologies,

3. Compare actual application rates to estimated quantities,

4. Conduct pavement infield performance testing to evaluate the performance of chip seal at one-year, and

5. Determine if projects constructed with close application rates to the rationally estimated rates performed better in terms of embedment and estimated lifetime.

5.2 Experimental Plan

Figure 5-2 shows the methodology employed to conduct various laboratory and field-testing required to feed the rational design computations, and the standards followed. First laboratory and field-testing were done on identified roadways to characterize the properties of used aggregates. Laboratory testing included specific gravity (G), absorption (A), loose unit weights (LUW), average least dimension (ALD), gradation, flakiness, and abrasion resistance.

Field-testing was conducted using sand circle test to measure the pavement macrotexture properties, namely mean texture depth at the pre-seal condition. After conducting laboratory and field-testing, design quantities were computed and compared to the actual application rates.
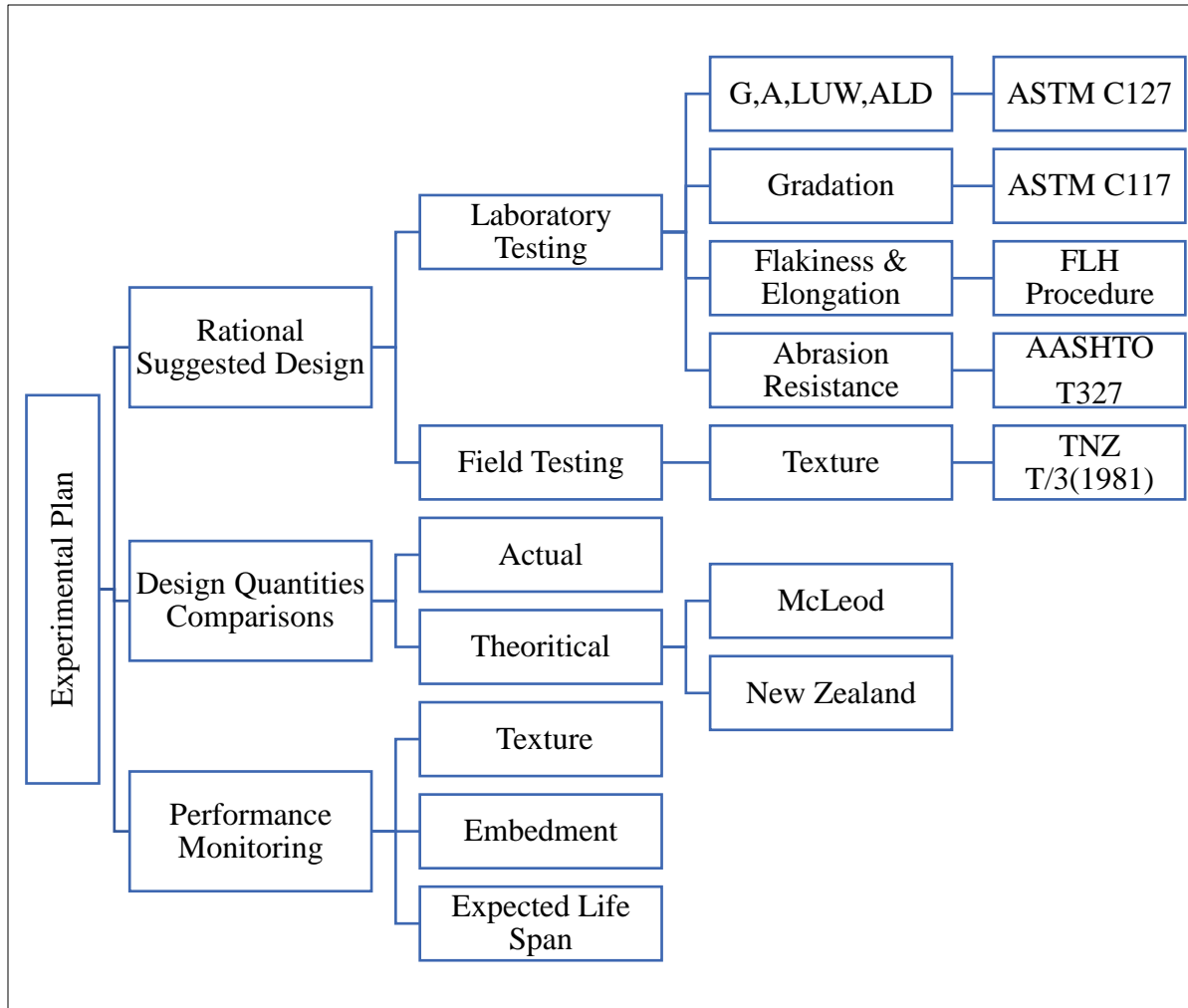
Figure 5-2 Methodology

Finally, comparisons are tied to performance to test the effect of material quantities on texture, embedment and expected life span, based upon pavement mean texture depth measurements at one year of roads' operation.

The study uses chip seal case studies to conduct materials quantities design analysis. Table 5-3 displays a summary of the characteristics of each of the eight projects used in the study. Traffic volume is identified as low if the AADT is lower than 500. Seal types used were either polymer modified emulsified asphalt (CRS-2P) or polymer modified hot applied asphalt (AC-15P).

Table 5-2 Summary of characteristics of chip seal test sections

Project Test Section	Traffic Volume	Binder Type	Aggregate application rate (kg/m^2)	Binder application rate (l/m^2)
TS-1	Low	CRS-2P	16.5	2.1
TS-2	High	AC-15P	10.3	1.6
TS-3	High	AC-15P	9.7	1.7
TS-4	High	AC-15P	10.8	1.6
TS-5	High	AC-15P	10.3	1.6
TS-6	High	CRS-2P	16.7	2.2
TS-7	High	CRS-2P	16.7	2.2
TS-8	High	CRS-2P	12.4	2.3

5.3 Rational Design Quantities Estimation

Rational designs calls for evaluating aggregate properties and use such data in the design process. Representative aggregate samples were collected from the case studies and tested in the laboratory. Aggregates were wet sieved, and their distribution showed that they were uniformly graded, which is ideal for chip seal application. Table 5-3 presents a summary of aggregates' physical properties. Aggregates are considered of good quality and suitable for chip seal application. In general, they had an acceptable amount of flat particles and good resistance to abrasion and impact forces when compared to the specifications (Shuler 2011).

Table 5-3 Aggregates physical and mechanical properties

Roadway	Median Size (mm)	ALD (mm)	Bulk Specific Gravity (SSD)	Voids in Loose Aggregates (%)	LUW	Abs. (%)	Abrasion Loss (%)	FI (%)
TS-1	6.35	5.08	2.615	0.47	86.9	2.01	6.09	13.1
TS-2	7.62	6.35	2.559	0.47	85.4	1.63	7.21	5.2
TS-3	7.62	6.35	2.559	0.47	85.4	1.63	7.21	5.2
TS-4	7.62	6.35	2.559	0.47	85.4	1.63	7.21	5.2
TS-5	7.62	6.35	2.559	0.47	85.4	1.63	7.21	5.2
TS-6	7.112	5.842	2.584	0.46	87.7	2.06	7.45	6.4
TS-7	7.112	5.842	2.584	0.46	87.7	2.06	7.45	6.4
TS-8	7.112	5.588	2.512	0.47	82.6	2.65	8.6	12.1

Projects' pre-seal texture condition is essential to calculate rational design estimates, while one-year post construction texture condition indicate chip seal projects' performance. Figure 5-3 shows the texture results of the observed pavements at their pre-seal condition and 1-year post construction condition. The study used testing results to back-estimate selected roadways' rational design quantities according to both McLeod and New Zealand procedures. Exact design calculations according to McLeod and New Zealand methods are shown in Appendix B.
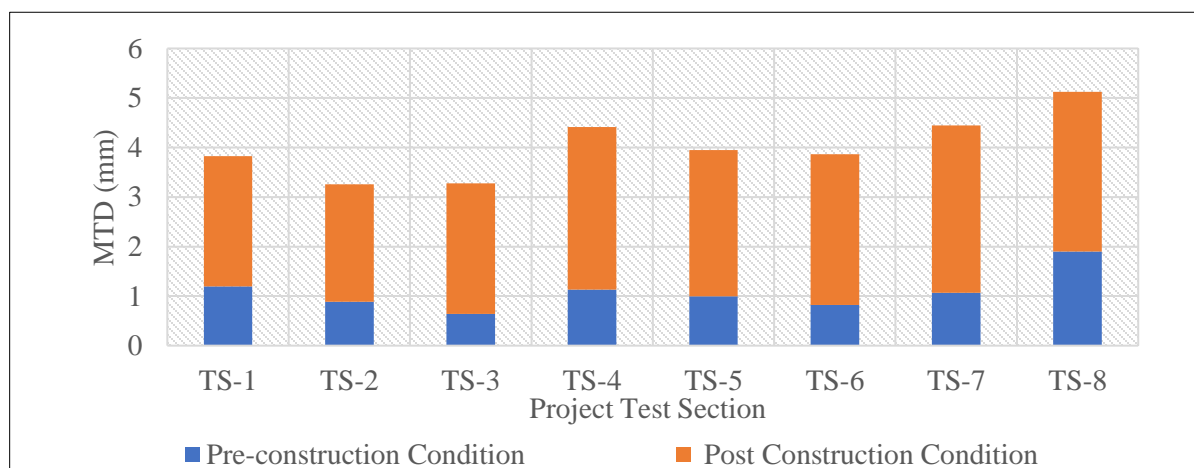

Figure 5-3 Texture at preconstruction & post construction condition

Figure 5-4 presents a comparison between aggregates' actual application rates and the rational design estimates. The average difference between the two rational design estimates is about 15 percent. This is expected due to factors slight variation between the two approaches. For example, McLeod provides texture correction factor based upon visual investigation of the pre-seal condition, while New Zealand provides texture correction factor based on field-testing. On the other hand, the small difference between the two rational design estimates could present a verification of the reasonability of both approaches.
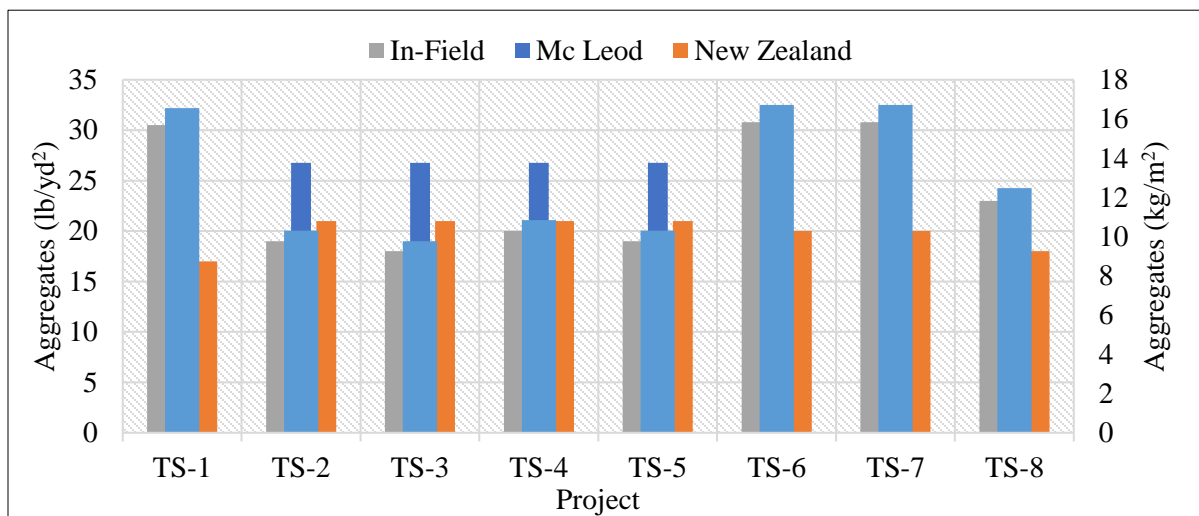

Figure 5-4 Aggregate application rates

Findings show that McLeod estimates are closer to the infield quantities when compared to New Zealand estimates. At close inspection of infield application rates, TS (2, 3 and 4) had much closer rates to the rationally estimated quantities, when compared to the other sections. While TS (1, 6 and 8) can be identified as relatively overly chipped when compared to the rationally estimated quantities. The use of rational design estimates should help in reducing the amount of over chipping in addition to costs reduction. Over chipping usually leads pavements to lose more surface texture and obtain less embedment, which ultimately leads to more aggregate loss.

Figure 5-5 shows a comparison between binder field application rates versus the two rational back estimated rates. New Zealand provided the highest quantities' estimates and was the closest to the infield quantities, in contrast to the aggregate application rate situation. At close inspection of infield application rates, Projects TS (2, 3 and 4) had much closer rates to rational estimates when compared to the rest of projects. TS (1, 6 and 8) can be identified as being treated with excess binder quantities. The use of rational design estimates should help save costs related to using excess binder materials and avoid problems such as bleeding.
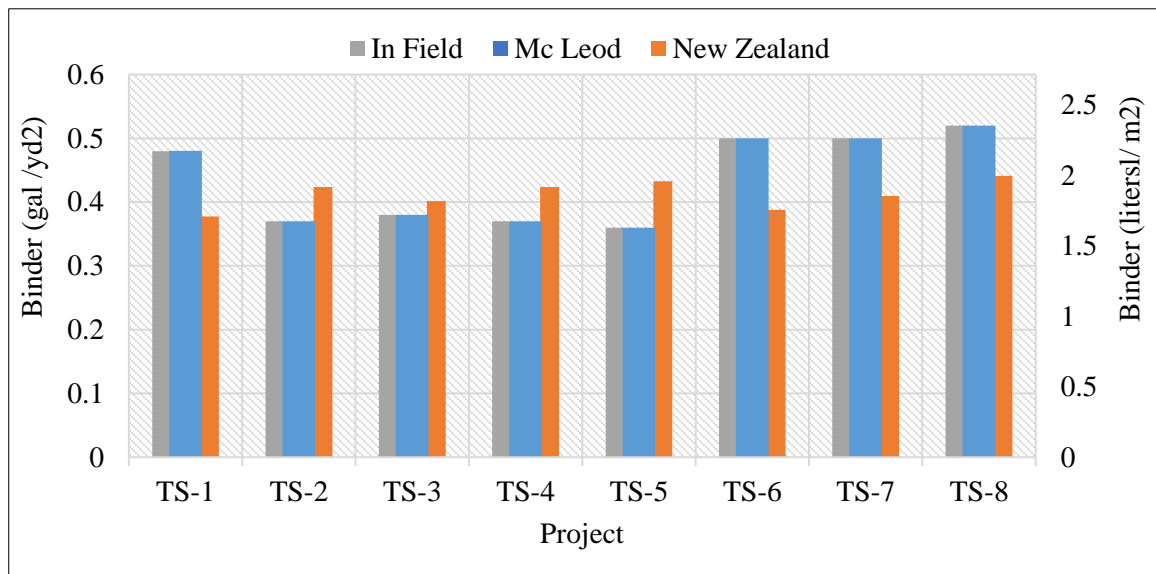

Figure 5-5 Binder application rates

Considerations for Possible Field Variations

It is necessary that the binder and aggregate application rates be appropriate during construction to achieve the optimum performance of chip seal. The optimal application rate is a function of various infield parameters such as traffic, pavement gradient and roads underlying condition (Shuler 2011). Rational designs consider various infield parameters, however, unforeseen conditions may take place and adjustments would be necessary, still in an engineered rational approach.

Minnesota seal coat manual indicates that binder quantities needed in the field are often higher than what is estimated in the design, up to a 15 percent possible variation. The manual advises using localized design charts as presented in Figure 5-6. The chart below shows the adjustment chart developed for Oregon selected projects that would correlate between field adjustments and estimated (theoretically computed) design rates. There is a trend between the changes of aggregate and binder field rates in comparison with New Zealand design estimates. A positive value indicates an added amount, and a negative value indicates a reduced amount.
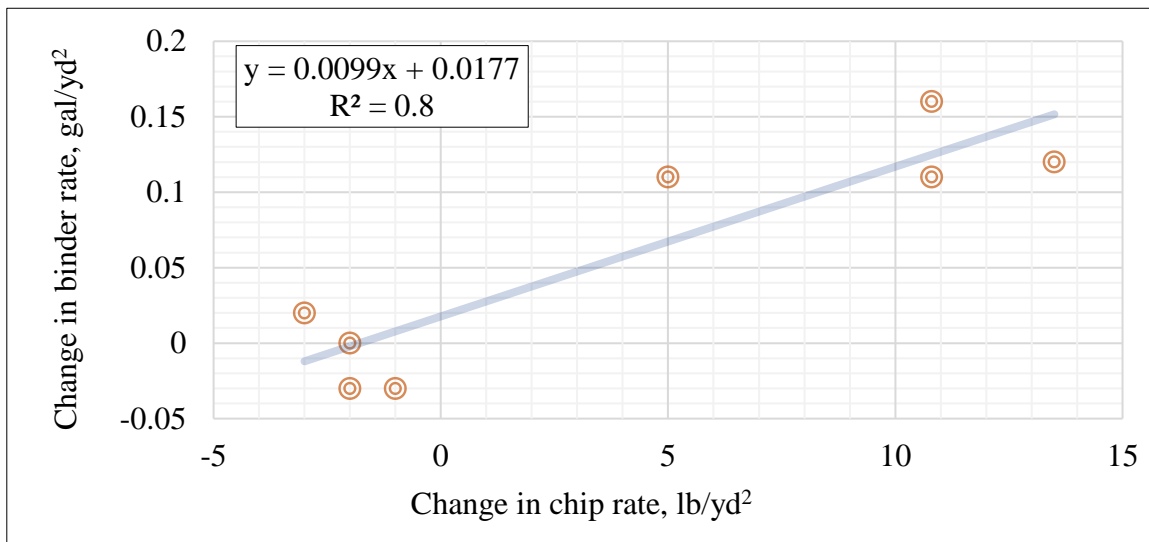

Figure 5-6 Field quantities adjustment chart (Field versus Theory)

The data indicates that if no changes in the chip application rates are required on site, the increased binder requirement may be around 0.01 gal/sy. The range of data shows 0.01-0.15 increase in binder rates based on differences between the field and theoretical rational design. The trend found is intuitive, because if the field requires more chips, the binder rate should increase as well to achieve the required embedment. Understanding the main concepts of chip seals would prepare contractors/agencies to act in a rational way instead of relying on their previous expertise, which might not yield promising results.

5.4 Correlation between Design and Field Performance

5.4.1 Embedment

Using rational approaches helps in reducing the amount of over chipping and/or binder excess, resulting in better performance and costs reduction. Based on performed comparative analysis, test sections TS (2, 3, 4 and 5) had the closest infield rates to the rationally estimated quantities regarding both their binder and aggregates' application rates. Results revealed that projects' test sections' TS (1, 6, 7 and 8) were found over chipped and with excess binder. Over chipping usually leads pavements to lose more texture and acquire lower embedment.

The embedment depth can be obtained from sand circle test results and aggregates' ALD (Shuler 2011). Performance based design specifies that aggregate embedment into binder should be about 70 percent after trafficking (Hanson 1934; McLeod et al. 1969). An appropriate amount of embedment will reduces aggregate loss but too much embedment will lead to flushing and possible texture problems (Gransberg and Zaman 2005). Figure 5-7 displays the percent embedment for all test sections at one-year post seal construction.
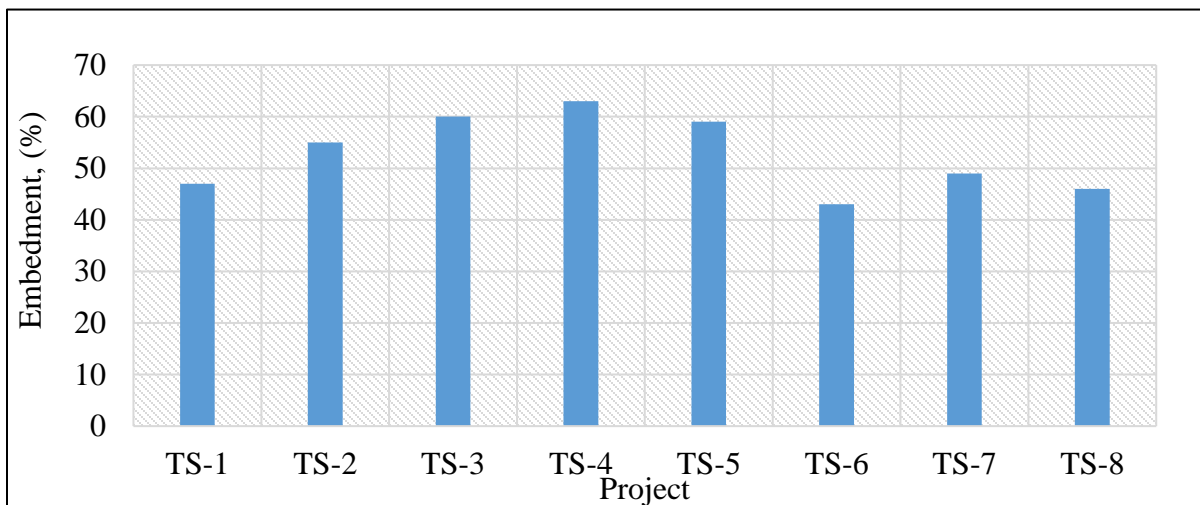

Figure 5-7 Test sections embedment

Results demonstrate that sections TS (2, 3, 4 and 5), identified as being applied with rational

aggregate and binder amounts, had higher embedment depth than the rest of test sections.

The rationally constructed roadways had an average embedment of 60 percent after one year

of the roadways operation. Roadways TS (1, 6, 7 and 8) have shown lower embedment

percentages, with an average value of 46 percent.

5.4.2 Estimated design life

New Zealand specifications have developed a texture performance specification to

determine whether a chip seal meets agency expectations or not. The performance metric is

based on the desired texture properties at the anticipated design life. After one year of service

life, the texture reduction due to traffic should not fall below a minimum requirement of 0.9

mm. Based on that requirement, New Zealand developed a deterioration model to predict the

expected design lifetime (Yd) based upon texture performance using Equation 5-9 (Buss et

al. 2016). The model considers that after one year of traffic, the pavement macrotexture must

be sufficient to ensure the texture changes have not reduced below the minimum

requirements.

$Yd = 4.916 + 1.68 (ALD) - (1.03 + 0.219\ ALD)\ \log_{10} (elv)$ Equation 5-9

Where,   Yd = design lifetime in years,

ALD = average least dimension (mm), and

elv= equivalent light vehicles per lane per day (where one heavy vehicle is assumed

to be equivalent to 10 light vehicles).

Figure 5-8 shows the estimated life span of roadways based upon New Zealand

deterioration model. Findings show that roadways constructed with rational amount of

materials, i.e. TS (2, 3, 4 and 5), yielded higher estimated design lifetime when compared to the rest of the roadways.

A key element when it comes to performance evaluation is to understand that current performance problems might lead to even more complex problems that would need more intrusive and expensive treatment solutions. For example, finding that some roadways have less embedment than required is not only about embedment problems, because less embedment would lead to more complex problems such as aggregate loss, aggregate-dislodgement, vehicles damage, flushing, reduced texture problems, reduced life time and possible seal damage.
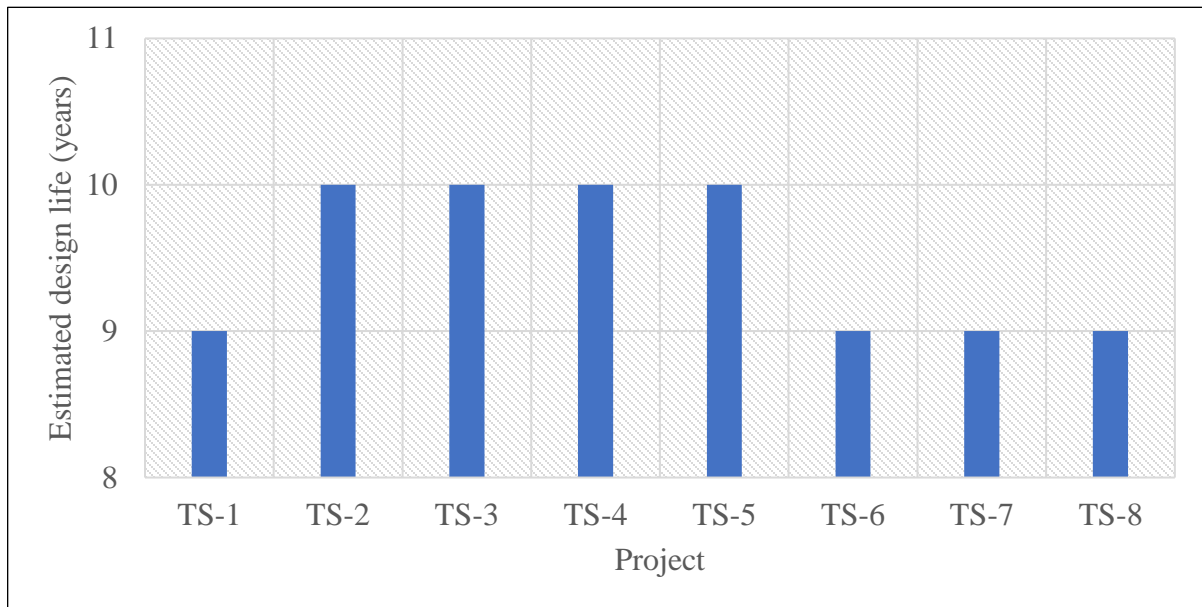

Figure 5-8 Test sections estimated design life time comparative analysis

5.5 Conclusions

Asphalt pavement research has progressed by improving methods of material characterization and performance monitoring. Many states collect pavement management information system data to track performance. Current chip seal design approaches have fallen short of implementing the newest findings on a national level. A major problem that

agencies meet when they try to implement a robust pavement preservation program is the lack of rational chip design methodology. Chip seal design requires understanding the properties of materials available to the project, as aggregates size, shape, gradation and binder type to estimate the proper chip seal design quantities. Following rational chip seal design approaches ensures that involved parties in chip seal project understand the basic fundamental concepts behind the design.

McLeod and New Zealand are chip seal rational design methodologies that require aggregates characterization and in-field experimentation to estimate the required quantities. The study selected various projects and back estimated their proper design quantities, and compared them to the actual application rates. Findings showed that roadways that were constructed with close rates to the rational estimated quantities had better performance than other roadways in terms of embedment and estimated design life.

5.6 Acknowledgements

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CHAPTER 6.   DEVELOPING MACRO TEXTURE LOCALIZED PREDICTION MODEL FOR CHIP SEAL PAVEMENTS SERVICEABILITY

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Modified from a paper submitted to International Journal of Pavement Engineering

Abstract

Pavement preservation techniques are used to sustain the performance of roads and extend their service life. Chip seal is known to be one of the most efficient and cost effective rehabilitation and maintenance techniques. This study proposes a methodology for predicting chip seal pavements service lives based upon local in-situ performance testing. The methodology is demonstrated through utilizing macrotexture performance-based data of fourteen US chip seal projects tracked over a two-year period, and use a regression model to predict their performance beyond the monitoring period. The approach is validated by comparing the developed prediction model to Oklahoma's chips seal deterioration model. Both models provided similar deterioration trends, showing that chip seal treatments can over exceed the literature expectations of 7-9 years, and can extend the life of asphalt pavements by an average of 10 years. A Survival study is further presented to predict chip seal life expectancy at different levels of survival probabilities. The performance of treatments can be associated with the owner's level of accepted risk (depending on the project's function and classification). Developing localized data platform will assist agencies and decision makers in pavement management systems to plan effectively and competently.

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6.1 Introduction

6.1.1 Background

Chip seal is a pavement preservation technique, which is applied to flexible pavements. The system consists of a single layer of aggregates that are embedded into the binder. Chip seals have been advocated because of their economic viability and ease of application (Karasahin et al. 2014). Research and practice proved that chip seal improves pavement performance in terms of texture properties, smoothness, skid resistance and impermeability. It further contributes to the delaying of binder aging, and the extension of the pavement life, while providing protection from traffic and climate exposure (Gransberg and Zaman 2005; Guirguis and Buss 2017; Karasahin et al. 2014).

6.1.2 Overview of Oregon's projects

Chip seals have been applied successfully to asphalt roads in Oregon for preservation and maintenance since the mid-eighties. The graph in Figure 6-1 shows historic mileage of chip seal construction for the last 30 years in Oregon (Ohio Department of Transportation 2018). With all chip seals application, two chip seal roadways in western Oregon have experienced failures within a year of their construction, raising awareness of chip seal's best practices and performance evaluation (Ohio Department of Transportation 2018).

In 2013, Oregon DOT recommended to conduct research on chip seal design methodologies and specifications. The goal was to apply quantitative measurements, which could potentially change chip seal industry from an "art to a science" by implementing post-construction long-term experimental plans to assess and evaluate chip seal performance.

Based upon studies and observations, (Gransberg et al. 2005) demonstrated that chip seal performance is a function of many parameters including design quantities, construction procedures, material's quality, work consistency, climate, and traffic conditions.

In addition, (Gransberg and Zaman 2005) studied 342 chip seal projects and reported that performance of seal coats depend heavily on the effectiveness of the aggregate to binder bond. The embedment of aggregates into the binder minimizes the occurrence of common problems such as loss of aggregate and skid resistance (Aktaş et al. 2013; Zaman et al. 2014). Such problems lead to the appearance of distresses such as bleeding and raveling. Both distresses causes more texture reductioon with time and result in pavements deterioration and reduce treatment's expected life.
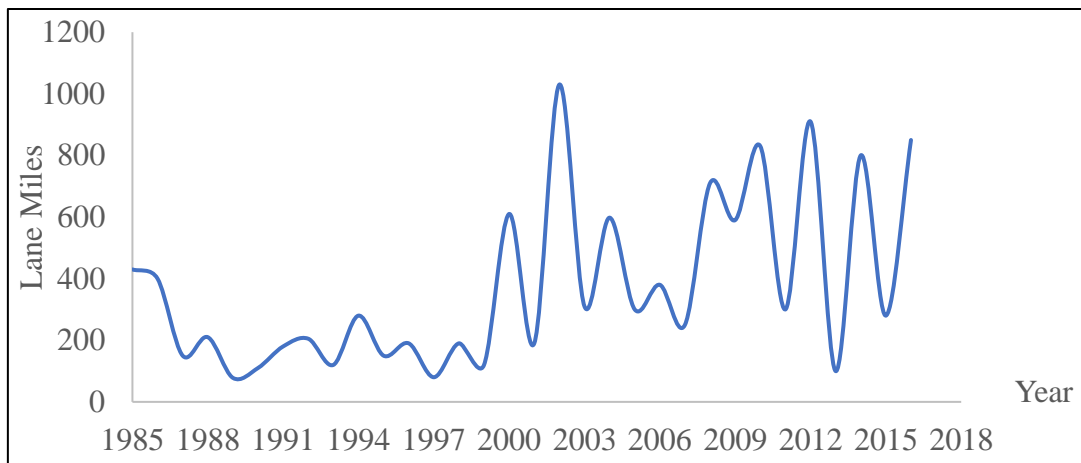

Figure 6-1 Oregon chip seal projects by lane miles (1985-2018)

6.1.3 Chip seal performance

Pavement texture is often categorized by texture wavelengths. The categories for texture wavelengths include: (1) mega texture of 50 to 500 mm wavelength, (2) macrotexture of 0.5 to 50 mm wavelength, and (3) microtexture of less than 0.5 mm wavelength (Henning et al. 2014). Microtexture is the measure of aggregate particles friction properties, while macrotexture is the measure of aggregates physical properties such as: size, shape and spacing (Pittenger and Gransberg 2012).

Microtexture and macrotexture surface properties deteriorate over time due to traffic and environmental exposures. Pavement managers usually assess chip seal performance by

monitoring their macrotexture deterioration rate. A remedial action is usually planned when the surface reaches a predetermined value (either assumed or empirically estimated).

6.1.4 Pavements prediction models

Traditionally, pavement prediction models either predict a condition value for a given pavement age, or predict the incremental change of the behavior/performance from one year to another (Henning and Roux 2008). Performance prediction models are used to (Pierce and Kebede 2015):

- Estimate future pavement conditions,

- Identify the appropriate timing for pavement preservation activities,

- Identify the most cost-effective treatment strategy on the network level,

- Demonstrate the consequences of different pavement investment strategies, and

- Plan future pavement programs.

Although traditional model types usually provide reasonable predictions, New Zealand Transport Agency (TNZ) reported differences between available prediction models and actual pavements performance. TNZ demonstrated that pavement conditions hardly change over time, but when they do, they deteriorate rapidly as shown in Figure 6-2 . This contrasts with traditional pavement model assumptions (Henning and Roux 2008). Developing pavement models based upon localized data platform will alleviate such problems and provide more practical and convenient way to predicate more accurate pavement performance.
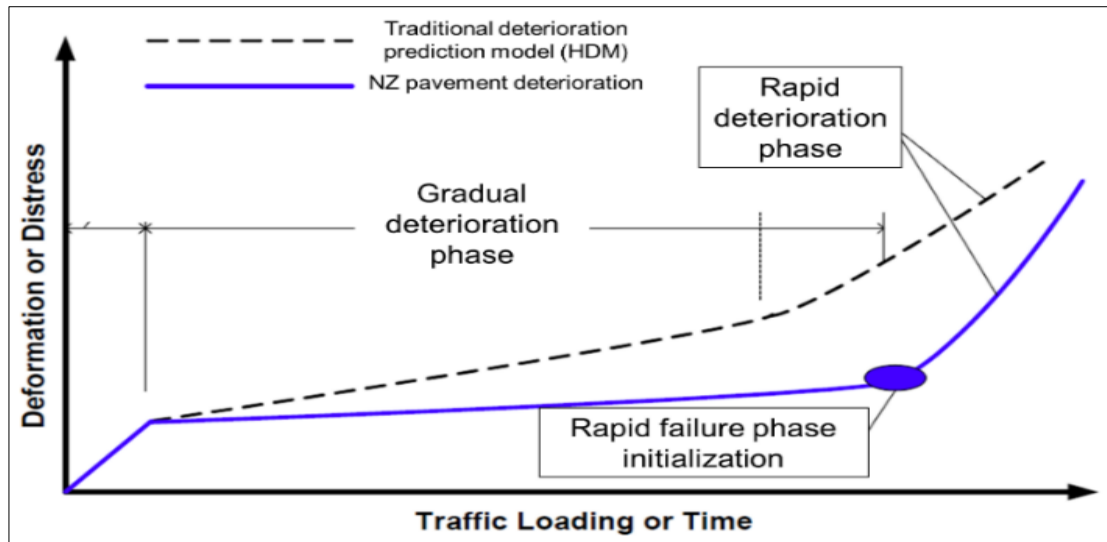
Figure 6-2 Pavement deterioration model (Henning & Roux 2008)

In addition, research has demonstrated that traditional methods used to evaluate asphalt pavement performance is not applicable to chip seal performance (Karasahin et al. 2014). The commonly used asphalt methods do not consider two common chip seal distresses, which are bleeding and raveling (Aktaş et al. 2013; Roque et al. 1991). The combined effect of both distresses causes pavements texture reductioon which affects the performance on the long run.

Research studies confirm that macrotexture properties of pavement surfaces considers the effect of both distresses (bleeding and raveling), because texture reduction is a result of both aggregate's wear and embedment problems (Aktas et al. 2013; Gransberg and James 2005). In Australia and New Zealand, extensive work has been done to manage chip seal pavements' performance based upon macrotexture properties, or mean texture depth (MTD) (Pittenger and Gransberg 2012). Gransberg's study (2007) has confiremed that measuring macrotexture surface characteristics of chipseal is considered reliable and objective method to evaluate and predict chip seal performance. Nationally and Internationally, macrotexture properties have proven to be a primary performance indicator for chip seals, that can be

measured and analyzed to determine the design remaining service life (Aktaş et al. 2013;
Buss et al. 2016).

6.1.5 Objectives and scope

The objective of this study is to build upon previous research that promotes the use of
localized chip seal pavements' macrotexture properties to develop performance deterioration
models. Developed model would serve as a management tool that estimates the expected
service life of chip seal treatments. The methodology is established using data from fourteen
US chip seal field roadways located in Oregon, that were proctored over a two-year period
(2014-2016) to:

1. Evaluate the performance of chip seal using texture parameters,

2. Use texture quantitative results to develop localized deterioration models,

3. Validate developed model by comparing to other literature models, and

4. Develop a probability of survival analysis.

Pavements management systems can be enhanced by incorporating "engineering-
based" performance data into their decision-making process. Developing a valid localized
data platform will assist agencies and pavement managers to better manage their resources.

6.2 Experimental Plan

Figure 6-3 shows the research methodology to reach the mentioned objectives. The
experimental plan was setup based upon previously conducted studies on chip seals
performance. The study uses laboratory and field-testing of chip seal roadways located in
Oregon to develop a localized deterioration model and validate it using previous models from
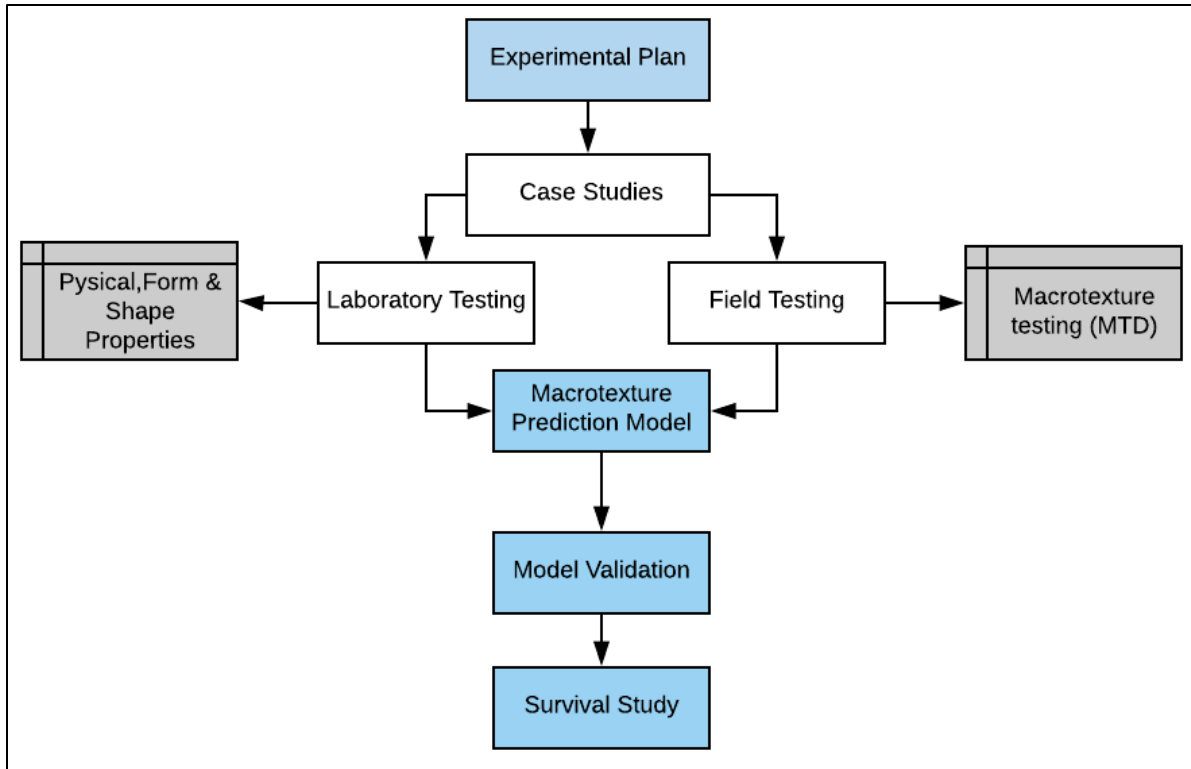the literature.

Figure 6-3 Outline of experimental plan

Laboratory testing is conducted to assess aggregates' properties and examine their viability to produce representative chip seal roadways. Periodic field-testing was conducted to determine the macrotexture properties using sand circle test in accordance with (TNZ T/3: 1981). Each roadway was divided into three 500-foot test section for experimentation purposes. Ten points were identified per roadway to conduct the sand circle test, 5 points between the wheel path (BWP), and 5 points in the outer wheel path (OWP). Testing was repeated at three different time points on each test-section at July 2014, July 2015 and July 2016.

Based upon MTD data, a regression model is used to approximate the deterioration rate and extrapolate the remaining service life of chip seal treatments. Failure criterion was identified based upon macrotexture properties of a value of 0.9 mm, consistent with TNZ P-12 performance specification (Pittenger et al. 2012).

Service life was determined by identifying the time it took each treatment to reach the pre-identified value of failure. The developed deterioration model would be compared to other literature developed deterioration models to validate and verify the approach. Finally, a survival analysis is presented to demonstrate the probability of failure based upon observed projects performance at each estimated lifetime.

Oregon Case Studies

Figure 6-4 shows projects sleeted for the analysis, identifying their location, seal-type, and traffic volume (AADT). Six hot-applied chip seal sections (shaded in grey) and eight emulsified chip seal sections (shaded in brown) were constructed and monitored as part of this study. The first ten roadways (from left to right) were constructed in June 2014, while the rest were constructed in June 2015. The underlying asphalt pavement condition varied from very good to fair structural condition at the time of construction. Selected roadways
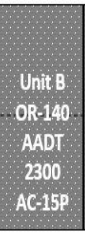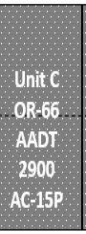

Figure 6-4 Case studies identification

have been exposed to the same climate conditions, but with varying traffic volumes. Two types of asphalt for seal coating were used, which are liquid asphalt (AC-15 P) and emulsified asphalt (CRS-2P/CRS-3P/ HFRSP2/HFE-100S). Both seal types were polymer modified to provide enhanced performance. In general, hot applied asphalt binder was used for heavier traffic volumes roads.

Chip seal materials were obtained from similar validated sources, and roadways were constructed in accordance with ODOT specifications. For hot applied seal roadways, the

aggregate and binder application rates were typically in the ranges of 20 lb/sq.yd and 0.36 - 0.4 gal/sq. yd, respectively. For emulsified seal roadways, the aggregate and binder application rates were typically in the ranges of 20-30 lb/sq.yd and 0.34-0.48 gal/sq. yd, respectively.

6.3 Results and Analysis

Aggregates used in selected projects were obtained and tested to evaluate their capability to produce good quality chip seal. Sieve analysis was performed, and all aggregates exhibited uniform gradation, which is ideal for chip seal application. Aggregates were also examined for flakiness and elongation. Aggregates had acceptable performance with an average flakiness index of 9 percent. Micro-deval testing examines the aggregate loss due to impact forces. ODOT specifies a maximum acceptance limit of 40 percent of aggregate loss to ensure a durable chip seal performance, and aggregates had an aveage weight loss of 7 percent which satisfies the specifications.

AIMS testing provide several useful parameters for determining aggregate shape, form and texture. In this study, aggregates' gradient angularity and sphercity indices were measured to assess their shape and sphericity properties. Results showed that according to AIMS specifications, aggregates used were found sub-rounded with modertae sphercity. This indicates that they are capable of forming good wearing surface when placed on the binder (Zaman et al. 2014).

Aggregates testing showed that aggregates used were of satisfactory qualities. Aggregates had good abrasion resistance and low flakiness potential. All aggregates shape and form properties were of allowable limits and satisfactory properties. Aggregate testing is vital in this study to verify that roadways studied can be used as representative population for other projects.

Figure 6-5 shows the mean texture depth results of studied roadways. Each roadway was investigated post the application of chip seal (within one week), at one-year and two-years post construction. Testing was done between the wheel path (BWP) and at the outer wheel path (OWP) with 30 replicates per roadway. Values of BWP and OWP were averaged to represent the MTD of the tested roadway.
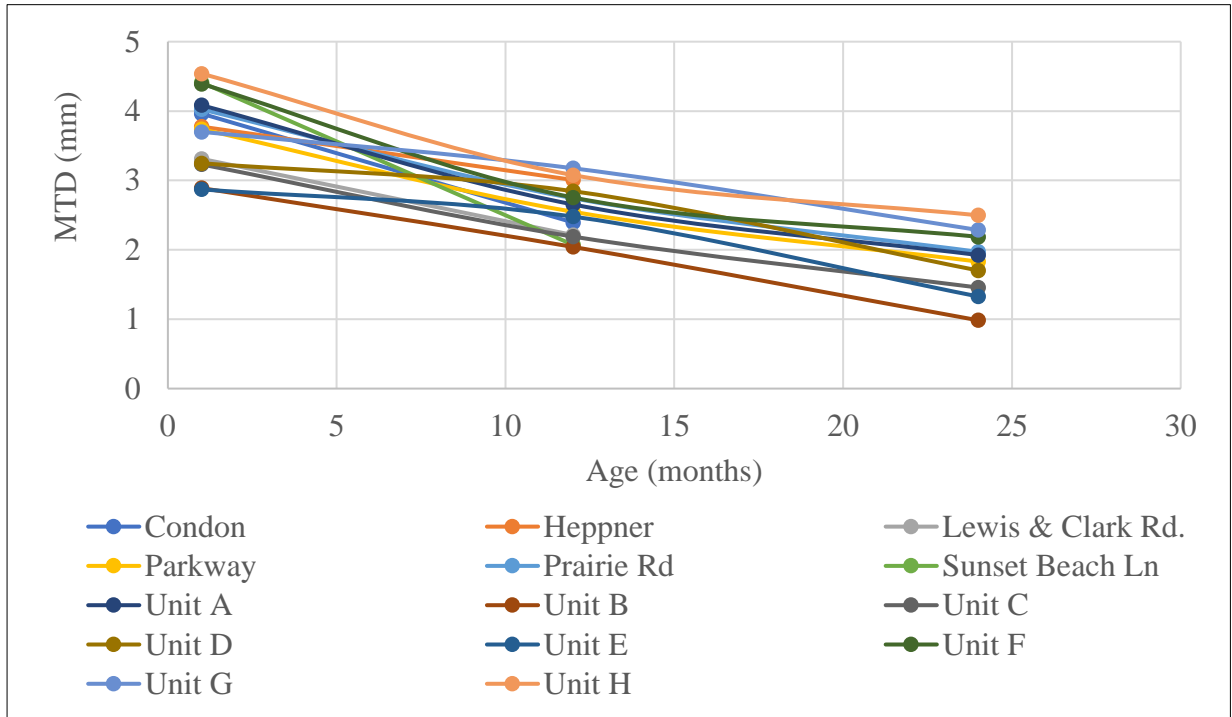
Figure 6-5 MTD performance of individual roadways

At close inspection, one could notice that all roadways had similar performance over time (i.e all performance lines have similar slopes). This indicates that they have very close, if not the same in few roadways, texture loss/deterioration behavior. This illustrates that chip seal roadways generally perform similarly when constructed with rational design and uses good quality materials and construction practices. Thus, the performance can be modelled and used to predict the performance of other chip seal projects.

6.4 Macrotexture Regression Model

Regression modelling is used to approximate the deterioration rate and extrapolate the remaining service life of chip seal treatment to determine the mode of failure. Regression modelling simply finds a function that approximates the relationship between the two variables (Age and MTD) based upon the input data. Failure criteria was identified based upon previous research using a minimum accepted MTD value. Estimated design service life was determined by identifying the time it took each treatment to deteriorate to reach the failure criterion benchmark, which is 0.9 mm, as specified by TNZ specifications.

Figure 6-6 displays Oregon roadways' macrotexture data used to approximate the deterioration rate of chip seal treatments, and extrapolate the remaining service life. The approach have been used and validated by previous studies (Aktaş et al. 2013; Pittenger and Gransberg 2012; Zaman et al. 2014).Based upon the average MTD data, a logarithmic regression equation with coefficient of determination (R^2 = 0.96) was developed to calculate the deterioration rate beyond the available 24-month data. These values were added to the actual data points to extrapolate the curve till it falls below the failure criterion of 0.9 mm, as shown in Figure 6-7.
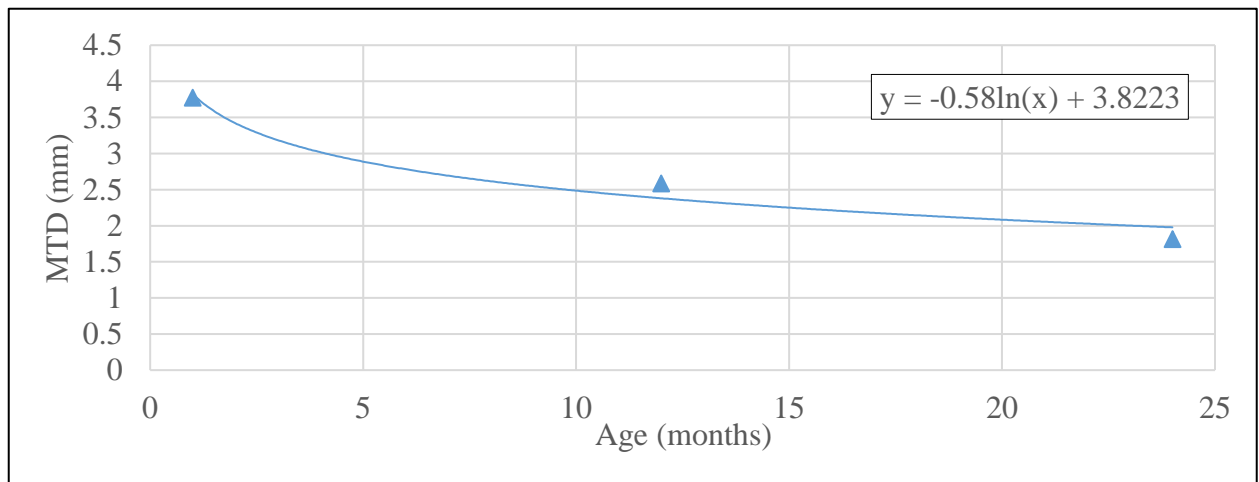
Figure 6-6 Average Oregon projects' MTD results

The findings of the deterioration model are based upon averaged data of 24- months MTD measurements that are extrapolated using regression modelling. The data are a result of different roadways constructed with varying sealant types, aggregates properties, underlying road conditions and traffic. This approach is validated by comparing the performance and deterioration trend of Oregon projects to other deterioration models that depended on longer periods of field measurements reaching 36 months (Pittenger and Gransberg 2012). Figure 6-7 shows that Oregon projects are estimated to require a remedial action after 13 years of their operation, which is consistent with Oklahoma's chip seal deterioration model findings, which provided an expected lifetime of 10 years for their roadways to require a remedial action (Gransberg et al. 2010). Both models' estimated service life of chip seals exceed the literature expectations of 7 years.
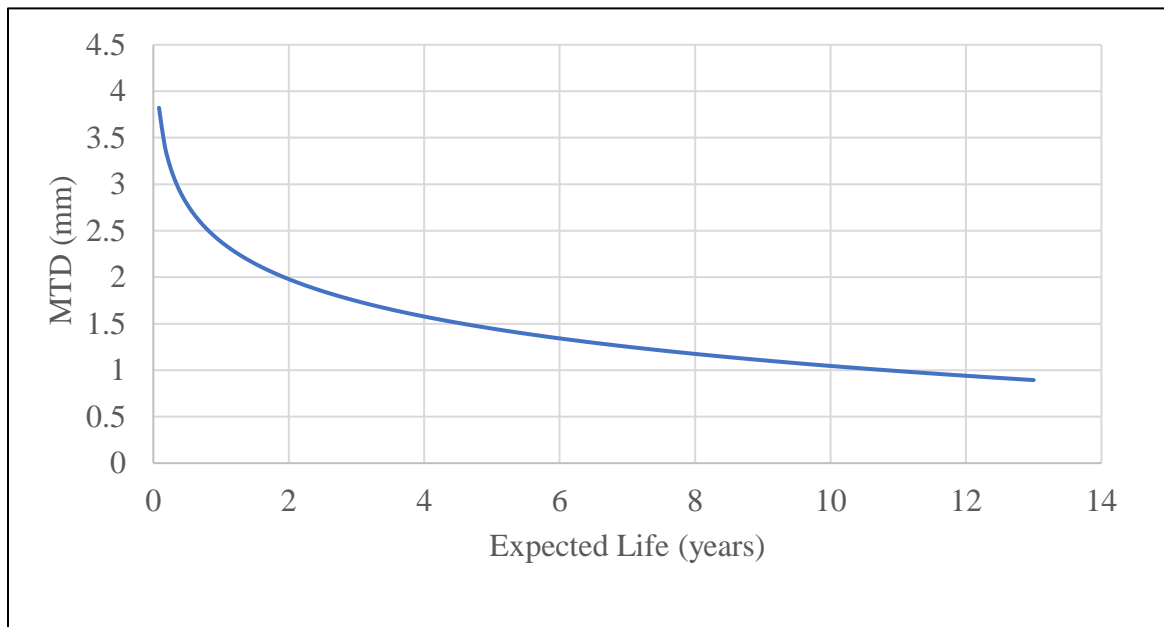
Figure 6-7 Chip seal prediction model

In addition, Figure 6-8 displays a comparison between Oregon and Oklahoma chip seal's prediction models (Gransberg et al., 2010). Oregon deterioration model is very close to Oklahoma's model with similar rate of texture loss. Oregon and Oklahoma estimated chip seal life span to be about 13 and 10 years respectively to reach the failure criterion of 0.9 mm.
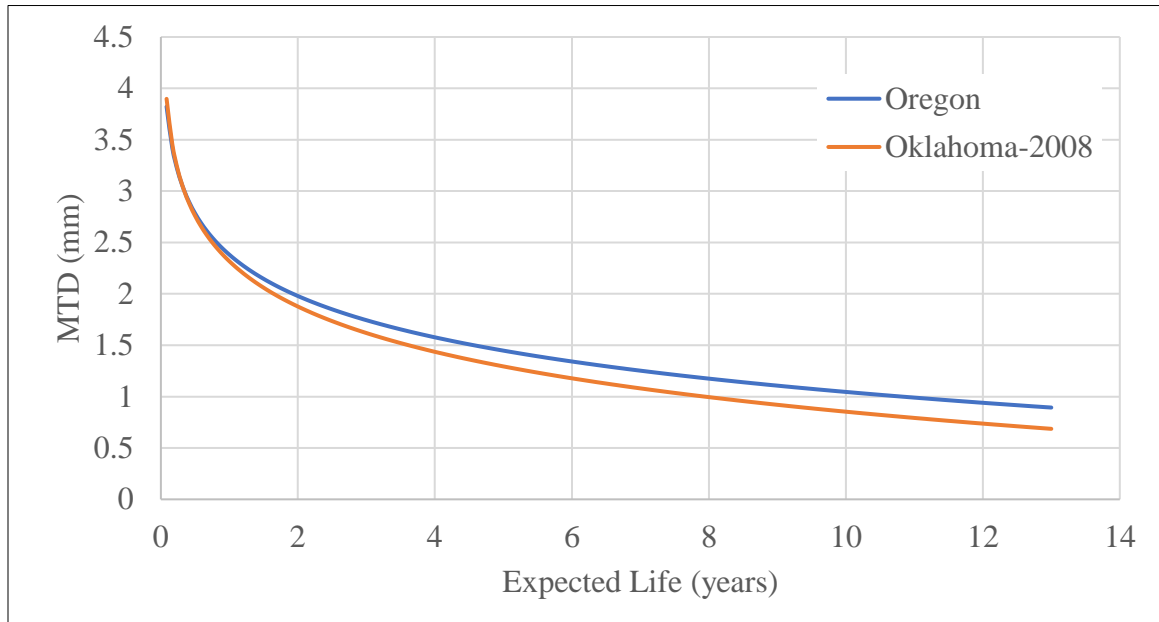
Figure 6-8 Comparison of chip seal prediction models (Oregon Vs Oklahoma)

At close inspection, both models reported the same initial MTD after chip seal application of 3.8 mm. In addition, both models estimated the same behavior for the first two years of roads' operation. However, the rate of deterioration varied starting the second year. Based upon Oregon projects performance, the model provided a lower rate of MTD loss than Oklahoma's model. Yet, as an overall evaluation, both models provided very similar trends of chip seal expected behavior along time.

Oklahoma prediction model provides a validation and verification of the study approach and findings. The study shows that current chip seal pavements performance have

been exceeding the literature expectations, and thus more research is needed to modify previously established models.

6.5 Survival Probability Study

A survival analysis was further developed using the Kaplan-Meier survival analysis method using in situ MTD measurements. Data points of individual roadway sections were used and extrapolated until they reached their identified failure condition. Accordingly, a survival probability was computed by recording the probability of chip seal roads to reach the treatment age with a minimum MTD value of 0.9 mm, as specified by New Zealand specifications (Pierce and Kebede 2015).

Figure 6-9 displays the survival probability curves based upon the performance of individual observed roadways in Oregon. A polynomial model was further fit through the average survival curve to determine the performance equation. The resulting performance curve and equation are shown in Equation 6-1 and Equation 6-2. Based upon resulting performance equation, a probability of failure graph was developed and displayed in Figure 6-10.

$S(P) = -0.173 \, \text{life}^2 - 0.9046 \, \text{life} + 102.59$ (with $R^2 = 0.95$)   Equation 6-1
$F(P) = 100(1 - S)$ Equation 6-2

Where, S(P) = survival probability

  Life = life expectancy (years)

  F(P) = probability of failure
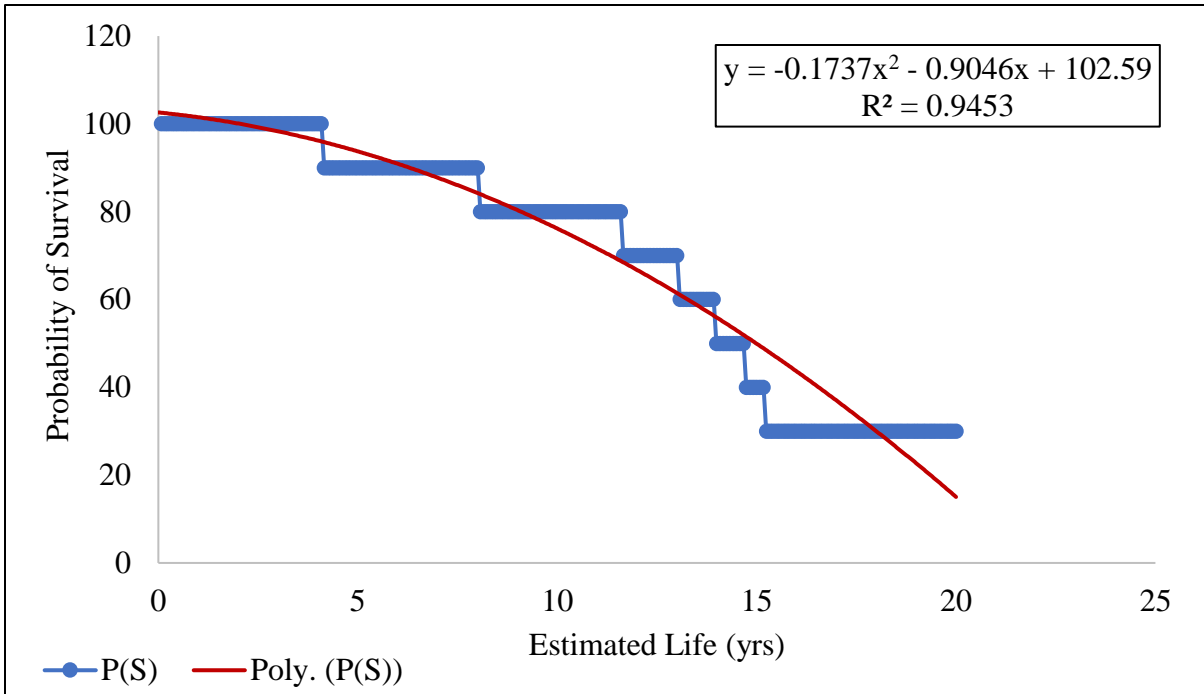
Figure 6-9 Probability of survival model
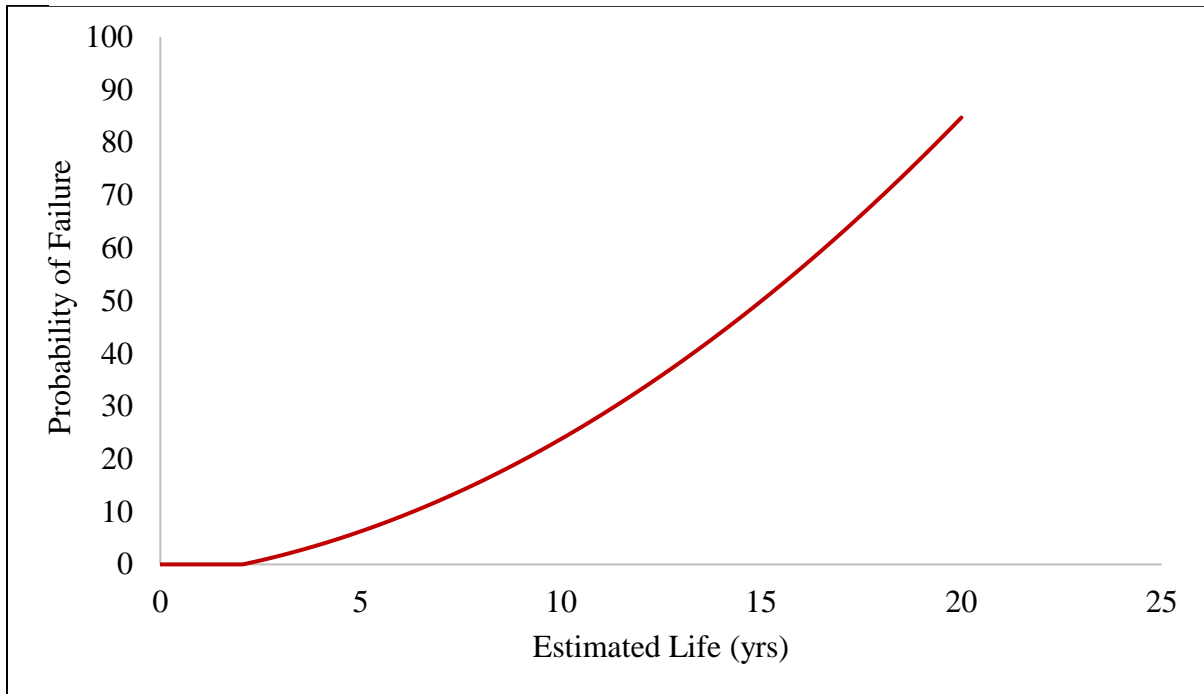
Figure 6-10 Survival probability

Most DOT's and pavement agencies recognize the importance of conducting survival probability analysis. The performance of treatments can be associated with the owner's level of risk depending on the roadway function and classification (Pierce and Kebede 2015). For example, for higher road classifications, agencies may want to minimize the risk of having a lower-than-expected performance by selecting a higher survival probability. For lower road classifications, where having weaker performance than expected would be less critical, a lower survival probability could be chosen.

Table 6-1 provides a comparison between Oregon developed survival model and three other chip seal's survival models namely, Morian et al., 2011; Liu and Gharaibeh 2013 and New Zealand model. The life expectancy was recoded at three different levels of survival probabilities (50, 60, and 80 percent), as shown in Table.

Table 6-1 Comparison of chip seals survival models

Chip Seals Projects Studied	Estimated Life at given Survival Probabilities (years)		
Probability	50 %	60 %	80 %
Oregon Model	15	13	9
(Morian et al. 2011) Model	11	10	6
(Liu and Gharaibeh 2013) Model	10	8	4
New Zealand model	10	9.5	9

The estimated survival probabilities of different models had variations. This is expected since estimated lifetime is affected by many factors such as pavement pre-seal condition, climate, traffic type, traffic volume, type, quality and quantities of applied materials….etc. Both (Morian et al) and (Liu and Gharaibeh) studies included projects located at different locations with variable climatic conditions, environmental zones, and

substrates condition, and this could explain why such models reported less estimated life span.

A general rematk is that most recently developed chip seal deterioration models have been reporting higher life expectancy than what the literature have previously provided. Most projects had a life expectancy exceeding 8 years (at 0.6 level of survival probabilities), which over exceeds the literature expectations. This might be incorporated to the advanced materials and best construction practices that have been evolving with time to enhance chip seal performance. However, this finding also shows the importance of updating current chip seal deterioration models preferably based upon localized performance data.

6.6 Conclusions

The study provides methodology to evaluate chip seal performance and utilize localized in-situ data to develop a deterioration model. The regression based model was developed to reflect localized conditions, and give realistic understanding of current chip seal performance, which has been exceeding the current literature expectations.

Performance data were collected from various Oregon field projects, and was quantified and fed to the deterioration model. The model was constructed using macro texture insitu testing of 14 US chipseal projects, that were periodically tested for 24-months period. The model was validated by comparing it to other previously presented deterioration models, and the performance trends were found very similar.

The same methodology was used to extrapolate the performance of selected roadways, and perform a survival analysis accordingly. The survival analysis was based upon Oregon identified projects. The analysis was presented to indicate the probability of survival of chip seal projects at a given treatment age.

Prediction of chip seals service life, based upon local performance data, would provide a better-quality insight for roads management systems to truly identify and justify their decision-making choices. The proposed platform can be further incorporated to feed other planning and/or scheduling platforms such as life cycle cost analysis models or agencies' budget allocation models. The framework is developed with the flexibility to include more technical data and extended testing periods for more customized performance trends.

6.7 Acknowledgements

6.8 References

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CHAPTER 7.   CONCLUSIONS

7.1 General Conclusions

The goal of this research is to assess the current state of chip sealing practices regarding design and performance evaluation. Research indicated that the lack of following a documented rational design computational method is a major concern in the industry. The non-existence of putting into practice short- term and long-term field performance evaluation in agencies' specifications is another concern.

Long-term quantitative test results of various chip seal roadways constructed in Oregon showed that chip seals were found effective in preserving their pavements by improving their surface microtexture and macrotexture properties during their two-year evaluation period. Chip seals have further protected the surface from additional cracking and deterioration. Parameters such as roadways' pre-seal condition, traffic volume and materials' types, materials' application quantities, and quality have all contributed to chip seal overall performance.

ANOVA study was used to understand the most significant factors that affect chip seal performance. Two factors were studied using a split plot repeated measures design, which are seal type and environmental aging effect. The study emphasized that emulsified and hot applied asphalts have provided their roadways with similar macrotexture performance. In contrast, environmental aging of pavements and its interaction effect with type of seal have proved to be statistically very significant.

The research further compared the selected projects' materials (aggregates and binder) infield application rates with the rationally back-estimated design rates for the same projects, while considering material properties and on-site factors. Findings showed that

projects constructed using appropriate application rates had better embedment and estimated life span when compared to the rest of projects that had excessive aggregate amounts and less binder content.

Finally, the study developed a localized macro-texture deterioration model based upon infield sand circle testing results, and findings revealed that chip seal treatments could over exceed the literature expectations. Chip seals can extend the life of asphalt pavements up to 10 years. The model is validated using another localized deterioration model developed for Oklahoma, which provided similar performance trend and findings. A Survival study is further presented to estimate chip seal life expectancy at different levels of survival probabilities. The localized data platform will assist agencies and decision makers in pavement management systems to plan effectively and competently.

7.2 Suggestions for Future Research

Chip seals can play an important role in the nation's pavement preservation program. Therefore, they deserve the same level of technical engineering support that is given for hot mix asphalt pavements. There is essentially a need for new updated research in pavement preservation techniques design and performance evaluation, including chip seals.

Chip seal design is an area that has great potential for enhancement. Most of the advancements in chip seal design has essentially ended in the United States by the 1960s, with McLeod proposed method. More research is needed to base chip seal design methods on sound engineering principles and technical design input data. Some advanced international design methods (e.g. New Zealand) require field surface condition tests, such as macrotexture and surface hardness to estimate their design rates. Thus, extensive research is needed on the feasibility of transferring such technology to the United States, and how to adapt such tests to the roads conditions in the U.S.

There is a strong need to conduct localized long-term field studies on chip seal to understand the effect of parameters on the service life performance. Factors such as pre-seal road condition, traffic volume, weather, construction and equipment practices, design rates…. etc. should be identified and correlated to performance. Well-designed statistical analysis should be employed to assess the significance of studied parameters. This will help local agencies to predict future performance of their roadways, and plan the next treatment in advance.

Extensive research is needed to develop chip seal laboratory tests that would correlate to field performance. Some tests are developed, yet, having a direct relationship to field performance, and having appropriate limits of tested parameters are still absent.

There is a strong need to quantify the disadvantages that results when using chip seals, such as noise level. A Research that studies the relationship between chip seal macro texture properties and noise emissions would be of great value to agencies and road management entities. Finally, there is a need to investigate design and performance aspects of other chip seals types such as: double seal, sandwich seal, inverted seal, or racked-in seal as well as the combination of chip seal used in tandem with other preservation techniques.

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APPENDIX A SAS CODES FOR SPRM AND TWO WAY FACTORIAL DESIGNS

A.1 SAS Code for SPRM statistical design (Chapter 4)

```
options formdlim = '-' nodate;
data chipseal;
  infile 'U:\Dissertation\chipseal\MTDresults' firstobs = 2;
  input $unit $seal MTD time;
proc mixed data = chipseal;

  model MTD = seal time seal*time / ddfm =  kr;
  random unit(seal);
  lsmeans seal time;
  lsmeans seal*time / slice = time;
  title 'slit-plot model';
run;
```

A.2 SAS Code for two-way factorial statistical design (Chapter 7)

```
options formdlim = '-' nodate;
data sweeptest;
  infile 'U:\Dissertation\chipseal\sweeptestresults' firstobs = 2;
  input $aggregate $binder weight loss;
proc glm;
    class aggregate binder;
    model weightloss=aggregate binder aggregate*binder;
lsmeans aggregate seal;
lsmeans aggregate*seal;
title 'sweep test results analysis';
run;
```

APPENDIX B CHIP SEAL RATIONAL DESIGN QUANTITIES CALCULATIONS

B.1 Obtaining Design Factors

Table B-1 Aggregate Properties for test sections

Test Section	M (mm)	FI	LUW	G	A (%)	ALD (mm)	V (%)
TS-1	6.35	13.1	86.9	2.615	2.01	5.08	0.47
TS-2	7.62	5.2	85.4	2.559	1.63	6.35	0.47
TS-3	7.62	5.2	85.4	2.559	1.63	6.35	0.47
TS-4	7.62	5.2	85.4	2.559	1.63	6.35	0.47
TS-5	7.62	5.2	85.4	2.559	1.63	6.35	0.47
TS-6	7.11	6.4	87.7	2.584	2.06	5.84	0.46
TS-7	7.11	6.4	87.7	2.584	2.06	5.84	0.46
TS-8	7.11	12.1	82.6	2.512	2.65	5.58	0.47

Table B-2 McLeod Correction factors for test sections

Test Section	T	E	S	A	R	P
TS-1	0.75	1.05	0.03	0.02	0.6	0
TS-2	0.6	1.1	0.03	0.02	1	0
TS-3	0.6	1.1	0.03	0.02	1	0
TS-4	0.65	1.1	0.03	0.02	1	0
TS-5	0.65	1.1	0.03	0.02	1	0
TS-6	0.6	1.1	0.03	0.02	0.6	0
TS-7	0.7	1.1	0.03	0.02	0.6	0
TS-8	0.7	1.1	0.03	0.02	0.6	0

Table B-3 New Zealand Correction factors for test sections

Test Section	AADT	Percent Trucks	HCV	elv	Tf	One year MTD (mm)
TS-1	460	10	46	437	1.9	1.19
TS-2	2300	10	230	2185	1.9	0.88
TS-3	2900	10	290	2755	1.9	0.64
TS-4	1280	10	128	1216	1.9	1.13
TS-5	1345	10	134.5	1277.75	1.9	0.99
TS-6	2650	10	265	2517.5	1.9	0.8
TS-7	670	10	67	636.5	1.9	1.06
TS-8	690	10	69	655.5	1.9	1.89

B.2 Calculations of Rational Design Estimates

Example of Calculations for TS- 1
1-McLeod Design
Design Steps:
STEP 1: Consider road and traffic correction factors (Table 1)
T= 0.75, E = 1.05, S = +0.03, P= 0
STEP 2: Perform Calculations using Equations

$$ALD = \frac{0.25}{1.139285+(0.011506)(13.1)} = 0.193 \text{ inch}$$

$$V = 1 - \frac{86.9}{62.4\ (2.615)} = 0.46\ \%$$

$$R = \frac{(2.244)(0.193)(0.75)(0.4674)+0.06+0.02}{1} = 0.23 \text{ gal/sq. yd}$$

$$A = 46.8 * (1 - (0.4 * 0.4674)) \times 0.193 \times 2.615 \times 1.05 = 20.16 \text{ lb /sq. yd}$$

3- New Zealand Design
Design Steps:
 STEP 1: Consider road and traffic correction factors:
T =0.6, E = 1.1, elv = 46, Tf = 437 and MTD = 1.19
STEP 2: Perform Calculations using Equations

$$e = 0.21\ MTD - 0.05 = 0.21\ (1.19) - 0.05 = 0.19$$

$$R= (0.138\ ALD +e)T_f = (0.138 *5.08+ 0.19)(1.9) = 1.69(\text{liter/m}^2) = 0.36 \text{ gal/ sq. yd}$$

$$A = 750 / ALD= 750 /5.08 = 147.63\ (\text{m}^2/\text{m}^3) = 17 \text{ lb/sq. yd.}$$