EVALUATION OF EFFECTIVENESS OF SEAL COAT TREATMENT USING FIELD DATA FROM LONG-TERM PAVEMENT PERFORMANCE PROGRAM

by

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DEDICATION

This thesis is dedicated to my family and all the professors who educated me. Without their patience, understanding and support, I would not have made it. I am grateful for their blessing.

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LIST OF ABBREVIATIONS

Abbreviation	Description
LTPP	Long Term Pavement Performance
LTPPM	Long Term Pavement Performance Maintenance
IRI	International Roughness Index
MRI	Mean Roughness Index
GRS	Geotextile Reinforced Seal
VIC	Victoria
ACT	Australian Capital Territory
NSW	New South Wales
QLD	Queensland

ABSTRACT

Over time, pavement deteriorates due to many factors such as weather, traffic, water infiltration, and degradation of the material. Pavement preservation treatment such as chip seal or seal coat treatment is a cost-effective alternative for extending the service life of asphalt pavement without the need for costly rehabilitation and reconstruction. However, many highway agencies in the United States do not use this potential approach to pavement maintenance. Therefore, there is a need for field performance-based study to develop a more fundamental understanding of the best practices for a seal coat treatment. Several factors such as asphalt binder and aggregate application rates, condition of existing pavement, amount and type of traffic, and environmental and drainage condition can significantly impact seal coat treatment performance. The thesis study analyzes and compares the effectiveness of chip seal treatments utilizing data obtained from the Long-Term Pavement Performance (LTPP) database in the United States and AUSTROADS database in Australia. A comparison between the United States method and Australia method is performed to evaluate the best chip seal design practice. The study further investigates the effectiveness of chip seal application and evaluates the effect of various parameters on chip seal performance. The study has identified that chip seal performance is mostly affected by key factors, which are underlying pavement condition, weather, and pavement age. Statistical methods are employed to conduct quantitative comparisons of performance before and after chip seal treatments and understand the significance of influencing factors on the performance.

1. INTRODUCTION

1.1. Overview

Seal Coat or commonly referred to as "Chip Seals" is one of many pavement preservation treatments used in the U.S. and worldwide. Seal Coat consists of a layer of asphalt binder (asphalt emulsion) that is overlaid by a layer of aggregate or chips embedded in the binder. Roads are used at an increasing rate not only in the U.S. but all around the world. Due to the combined effects of traffic and climate over time, the rate of deterioration in the pavement has been increased. In order to reduce the rate of deterioration or failure in pavements, pavement maintenance treatments such as chip seals are used, which are not only a cost-effective alternative to defer reconstruction or rehabilitation but also provide a number of enhancements to the pavement performance by sealing the surface from water, preserving existing structural strength and extending the service life of pavements.

Despite the considerable effect of pavement preservation programs on extending the service life of pavements, premature failures still happen. The factors responsible for these failures could fall into one or more of the following stages in production: existing pavement condition, traffic, material properties, climate, and construction. Different states in the United States have taken tremendous research efforts to develop laboratory tests and specifications for seal coat binders and aggregates, respectively. However, most of the recent studies are on the material side, and there is a need for quantitative studies to evaluate the effectiveness of seal coat treatments more comprehensively. Moreover, chip seals are not used frequently by all states in the U.S. on high traffic volume facilities because of the poor performance of a significant number of chip seals. As a result, many agencies refuse to use this potential approach. However, it seems that in other countries such as New Zealand and Australia, chip seals have performed quite effectively both on rural and urban roads and even in dense traffic areas. The main objective of this research is to quantify the effectiveness of seal coat treatment (under different climates and traffic loads) in terms of pavement performance and to find out the possible contributing factors that influence the performance of seal coat treatments. Also, the performance of seal coat on two different countries are compared to understand the effect of differences of techniques in performance of chip seals.

F.M. Hanson (1934) was the first to publish a rational design of seal coat treatment. In his work, he introduced a concept that a successful seal required the partial filling of voids in the covering aggregates. Hanson also indicated in his research that there will be 50% of voids in aggregates when first placed in the binder, which is reduced up to 30% by construction rolling and then the remaining 20% is reduced by traffic compaction. On the contrary, the current seal coat design method in New Zealand considers that the seal settles into the binder after approximately one year, which provides a new consideration of accepting performance within the first twelve months since construction to avoid agency loss due to premature failures. Therefore, with this consideration, the objective of this study is to evaluate the effectiveness of seal coat treatment by comparing pavement performance before and after the application of treatment in terms of different distresses measured in pavement field.

In this study, field measurement data from the Long-Term Pavement Performance (LTPP) database in the United States and AUSTROADS database in Australia are used to evaluate chip seals' performance. The effectiveness of treatment is measured from the performance change or reduction in deterioration rate are observed in different distresses on pavements such as alligator cracking, transverse cracking, longitudinal cracking, rutting, and international roughness index (IRI) data which are retrieved from the LTPP and Austroad databases. The research uses statistical methods to analyze the United States and Australia's pavement sections, which are treated with seal coats. An analysis is done based on performance change in these pavement distresses. And the result provides the idea of how this treatment is performing over time and helps to find out the factors that significantly impact the overall performance of the chip seals.

1.2. Objective of Thesis

The main objective of this thesis is to evaluate the performance of the seal coat treated pavement sections using field data in US LTPP database and compare the performance with Australia seal coat treated sections. Moreover, the evaluation of performance before and after the treatments helps to find the performance improvement and deterioration of the treated pavement sections over time in terms of the distresses measured on the pavement surface. Therefore, Statistical methods such as regression analysis, analysis of variance are employed to understand the effect of age, existing pavement condition, average annual daily traffic, and environment on the treatment effectiveness. Distresses such as alligator cracking, longitudinal cracking (wheel path and non-wheel path), transverse cracking, rutting, international roughness index, raveling, and bleeding are considered in this study.

1.3. Organization of Thesis

In this research, the effectiveness and performance evaluation of chip seals are conducted using the field data from the US LTPP database and Austroads database. Chapter 1 Introduction presents an introductory description that includes an overview, thesis objective, and the organization of thesis.

Chapter 2 Literature Review provides a brief background on chip seal treatment, construction and design methods used in the US and Australia, benefits of using chip seals, and different types of chip seals currently used on pavements. Chapter 2 also includes a review of current literature on the concept and effectiveness of preventive maintenance treatment, the effectiveness of chip seal treatment, different field evaluation studies carried out along the time.

Chapter 3 Data Synthesis and Analysis begins with a description of datasets from the LTPP and Austroads databases, which are the basis of this study along with data collection, extraction, and organization of the chip seal data. Also, chapter 3 explains the statistical methods used for analyzing treatment effectiveness or performance evaluation of chip seals.

Chapter 4 Results and Discussion presents the statistical analysis results of the distress data from field performance evaluation of chip seal treatments in the two different countries.

Chapter 5 Conclusions summarizes the research findings that are developed from the thesis research and recommendations for future studies.

2. LITERATURE REVIEW

2.1. Definitions and Benefits

A Chip Seal is a seal coating treatment that consists of a layer of bitumen which is immediately followed by the application of a layer of crushed aggregates. Chip seals are economical surfacing that is used effectively as treatments on roads carrying several thousands of vehicles per day. Chip seals, also known as seal coat treatment, bituminous surface treatment (BST), and sprayed seals (Australia) are relatively inexpensive surface treatment techniques that are highly effective in preserving pavement surface and extending the service life of the pavement. The procedure for seal coating of the pavement is straightforward which consists of different steps.

a) Seal severe cracks and repair load-related distresses before the application of chip seals.

b) Clean the pavement surface before construction.

c) Spray asphalt binder and spread the aggregate on top of it.

d) After spraying, rolling is applied to help the chips or aggregates embed into the binder properly.

e) Give the seal coated surface some curing time before opening to traffic.

f) Finally, the seal coated pavement surface is broomed to remove any loose aggregates.

As simple as the construction process seems, it requires appropriate engineering techniques to provide better performance. Depending on the application and type of seal, a seal coat treatment may be used as an initial seal, secondary treatment, or retreatment.

Initial Seal: An initial seal is an initial treatment, applying a seal coat treatment to a prepared base course, which has not been primed. These are termed 'first coat seals' in

New Zealand. It is intended that the seal adheres to the base, whilst providing a wearing course for traffic.

Secondary Treatment and Retreatment: A secondary or retreatment is the application of chip seals over an existing bituminous surface (e.g. a seal, original surface layer, asphalt overlay).

The types of seal coat treatments are based on the number of applications of seal coats in the sequence of the application of binder and the application of aggregate, which are described as follows:

1) Single/ single seal: A single/single seal consists of a single layer of binder, covered by a single layer of aggregate. This is a common type of chip seal treatment and is typically used in low traffic and low-stress environments.

2) Multiple-layer Applications: Seal Coat treatments may consist of applications of multiple layers of binder and/or aggregate. Some of the most common multiple-layer chip seal applications are described below. There are still different combinations of applications of chip seals which are possible for construction and may be explored by innovative practitioners. Multiple-application seals provide a robust and heavy-duty surfacing.

- Double/double seal: A double/double seal consists of a layer of binder followed by an application of a layer of large-sized aggregate. Then, suitable rolling and sweeping are done. After that another lower application of binder is applied followed by the spreading of a layer of smaller aggregate. The smaller aggregate fits into the spaces between the larger aggregate and locks it into place. This type of treatment is basically used to reduce the embedment of the smaller (second) aggregate into a flushed surface or soft base.

- Single/double seal: A single/double is a variation of the double/double seal. It is constructed by spraying a single layer of bitumen, spreading the large-sized aggregate at a more open spread rate than for a single/single seal and, before rolling is complete, spreading another layer of smaller aggregate. The smaller aggregate fits into the spaces between the larger aggregate and is locked into place by a small amount of bitumen (from the first spray). In a single/double seal, the second aggregate application is a permanent and integral part of the seal. This treatment is also named 'racked-in' chip seals. These types of chip seals reduce the traffic delays period due to construction. A racked-in seal is not so dependent on traffic compaction to obtain strength.
- Inverted seal: An inverted seal is a double/double seal that is 'inverted' from the normal double/double seal, which means that the smaller-size aggregate is on the bottom coat and the larger-size aggregate is on the topcoat. Both applications are normally placed on the same day. An inverted seal can be used to treat surfaces with large variations in transverse surface texture. It may also be used to reduce the risk of embedment of the larger aggregate into soft pavement materials.
- Sandwich Seal: Sandwich seals also referred to as a 'dry matting' in Australia. Sandwich Seal is a technique that involves the use of two applications of aggregate sandwiched around a single application of binder. These type of seal treats stripped or partially stripped seals or flushed bituminous surfaces.

- Geotextile Reinforced Seal: Geotextile reinforced seals (GRS) are produced by spraying a layer of bitumen onto a pavement (bond coat), then covering this bitumen with a layer of geotextile and lightly rolling. GRS can be used to provide more robust waterproofing and is considered as the most effective technique when treating badly cracked and distressed bound and unbound pavements. Geotextile seals are more sensitive to weather conditions during and several weeks after construction, and as such they should be programmed to allow trafficking in warm weather.
- Cape Seal: Cape seals were developed and first used in the Cape Province of South Africa. They are constructed by applying a single/single seal to the pavement (usually using a size 14 or 20 mm aggregate) followed by a slurry (or microsurfacing) that can either partially fill the void space between the bitumen and the top of the aggregate, or completely cover the top of the aggregate. This is achieved by either a single or double application of slurry. This type of treatment provides a very robust surfacing and the surface characteristics are substantially those of slurry. It has been used in rural areas to provide a surfacing with high shear resistance, comparable to that of asphalt, but in areas where asphalt is not economically viable.

The above illustrated types of chip seals are the most commonly used in Australia and some of them are also common in the United States. However, there are also several other types of chip seal treatment which can be constructed using various techniques and materials. The different types are:

a. Scatter coat
b. Aggregate Retention Seal

c. High Stress Seals (HSS1 and HSS2)

d. Extreme Stress Seal (XSS)

e. Strain Alleviating Membrane (SAM)

f. Fiber Reinforced Seal (FRS)

These various types of application of chip seals are used after the careful assessment of pavement sections, which will receive the treatments. Several parameters such as traffic volume and speed, existing surface condition (crack type and severity levels), performance requirement of the pavement (to provide better skid-resistance, reduce noise, seal minor cracks, protect the underlying surface layer, appearance (aesthetic), availability of material, equipment and expertise are carefully considered to select the most suitable seal coat treatment for a particular situation.

2.2. Chip Seal Design Methods

Chip seals have been in use since 1920s. Early uses were as a wearing course in the construction of low-volume gravel roads. Chip seals have 50 years of recorded history in the United States (Jackson et al., 1990). Hanson (1955) and Kearby (1953) developed strategies for chip seal design more than 65 years ago. The McLeod chip seal method is the most widely adopted approach to chip seal design (McLeod, 1960), and Epps proposed a further modification to the design method in the early 1980s . Different countries such as Australia, Canada, New Zealand, South Africa, the United Kingdom, and the United States have conducted in-depth studies for chip seal design (Gransberg & James, 2005; Hanson, 1934). Hanson was the first to articulate a design procedure for this technique with the concept involving the calculation of voids between the aggregates as a function of aggregate size (average least dimension (ALD)) and filling a portion of these voids with an amount of binder after traffic loads (Hanson, 1934). This remains the basis of seal coat design to this day, although with significant adjustment for changes in traffic loads and improved understanding of other factors influencing chip seals behavior.

The two widely accepted chip seal design methods used in the US are Kearby method and the McLeod method. Although a few agencies in the US have also developed their formal design procedures that are not based on either of the two methods, most use either an empirical design method or no formal method at all. The early practitioners of surface treatments or seal coats appear to have used a purely empirical approach to their design. Table 1 shows the percentage of US states using various chip seal design methods (NCHRP, 2005).

Table 1. Chip Seal Design Methods in the United States

Chip Seal Design Method	**United States (%)**
Kearby/Modified Kearby	7
McLeod/Asphalt Institute	11
Empirical/past Experience	37
Own Formula Method	19
No formal method	26

Australia, New Zealand, and South Africa have also developed engineering-based chip seal design methods for use in their respective countries. Australia's is called Update of Sprayed Seal Design Method (Austroads, 2006). McLeod design method and Australian design method, both have their calculation based on aggregate size and shape, texture, existing pavement surface, and traffic conditions. However, some of the calculations are similar in both countries. But Australia has an advanced method because of the common use of seal coat in most of the roadway with different materials, types of application depending on the traffic levels, the severity of pavement distresses, and weather. This chapter introduces both the Australian design method and McLeod method for calculating application rates.

2.2.1. McLeod Design Method

In 1969, Norman William Mcleod presented a design method for calculating asphalt and aggregate application rates, which is based on two basic principles:

- The application rate of a given aggregate should be determined such that the resulting seal coat will be one-stone thick. This amount of aggregates will remain constant, regardless of the binder type or pavement condition.
- The voids in the aggregate layer need to be 70 percent filled with asphalt for good performance on pavements with moderate levels of traffic.

The application rate of binder is determined by aggregate characteristics, traffic volume on the roadway, existing surface conditions, and residual asphalt content of the binder. The aggregate application rate depends on aggregate characteristics and traffic volume on the roadway. The factors for aggregate characteristics are introduced in the following paragraphs.

a) Median Particle Size (mm): The Median Particle Size (M) is determined from the aggregate gradation chart. It is the theoretical sieve size through which 50 percent of the material passes.

b) Flakiness Index: The flakiness index is a measure of the shape of the aggregate which determines the percentage of aggregate that is flat and elongated. It is determined by testing a sample of the aggregate particles for their ability to fit through a slotted plate. The plate has five slots in it for different sieve sizes: 4.75, 6.3, 9.5,12.5, and 19 mm. Slot number 1 is for chips retained on the 4.75mm sieve and so on (Janisch & Gaillard, 1998). The chips are considered flat or elongated if they fit through the slots. Flakiness index is calculated by:

$$FI = W_F / W_C \quad (1)$$

where,

W_F = weight of flat and elongated particles in the sample (kg)

W_C = weight of all particles in sample (kg)

c) Average Least Dimension (ALD), H (mm):

The average least dimension is determined by the median particle size and the flakiness index. It represents the expected seal coat thickness in the wheel path where traffic forces the aggregate particles to lie on their flattest side. The ALD is calculated by:

$$H = \frac{M}{1.139285 + (0.011506)FI} \quad (2)$$

where,

H = Average Least Dimension, inches

M = Median Particle Size, inches

FI = Flakiness Index (%)

d) Loose Unit Weight of the Cover Aggregate:

The dry loose unit weight (W) is determined according to TxDOT Test Method Tex-404-A and is needed to calculate the voids in the aggregate in a loose condition. It depends on the gradation, shape, and specific gravity of the aggregate.

e) Voids in the Loose Aggregate (% decimal):

Voids in the loose aggregates estimate the voids between the aggregates once they have been applied by the chips spreader and before they are rolled. Generally, this value will be near 50 % for one size of aggregate and less for graded aggregate. After initial rolling, the voids are assumed to be reduced to 30% and will reach a lower value of about 20 percent after sufficient traffic has oriented the stones on their flattest side. However, if there is not enough traffic, there will still be 30% voids present, and the seal will require more binder to ensure good aggregate retention. The following equation is used to calculate the voids in the loose aggregate:

$$V = 1 - \frac{W}{1000 * G} \quad (3)$$

where,

W = Loose unit weight of aggregate (kg/m^3)

G = Bulk specific gravity of aggregate

f) Aggregate Absorption (% decimal):

Most aggregates absorb some of the binder applied to the roadway. The design procedure should be able to correct for this condition to ensure enough binder will remain on the pavement surface. McLeod suggests an absorption correction factor, A, of 0.02 gal/SY if the aggregate absorption is around 2 percent (as determined from Tex-403-A). In the Minnesota Seal Coat Handbook (MnDOT, 2006), it is recommended that a correction factor of 2 percent be used if the absorption is 1.5 percent or higher.

g) Traffic Volume:

The traffic volume in terms of vehicles per day plays a role in determining the amount of asphalt binder needed to sufficiently embed the aggregate. Typically, the higher the traffic volume, the lower the binder application rate. At first glance, this may not seem correct. However, it is known that traffic forces the aggregate particles to lie on their flattest side. The particles would be lying in the same orientation if the roadway had no traffic as when they were first rolled during construction. As a result, they would stand taller and need more asphalt binder to achieve the ultimate 70 percent embedment. With enough traffic, the aggregate particles will lay as flat as possible causing the seal coat to be as thin as possible. If this is not taken into account, the wheel-paths will likely bleed. The McLeod procedure uses Table 2 to estimate the required embedment, based on the number of vehicles per day on the roadway.

Table 2. Traffic Correction Factor, T

Traffic Factor (Traffic-vehicles per day)				
Under 100	100 to 500	500 to 1000	1000 to 2000	Over 2000
0.85	0.75	0.7	0.65	0.6

h) Traffic Whip-Off:

The McLeod method also recognizes that some of the aggregate will get thrown to the side of the roadway by passing vehicles as the seal coat is curing. This loss is related to the speed and number of vehicles on the new seal coat. To account for this, a traffic whip-off factor (E) is included in the aggregate design equation. A reasonable value is to assume 5 percent for low volume, residential type traffic, and 10 percent for higher speed roadways.

McLeod Seal Coat Design Equations

The equations that are used to determine the aggregate and binder application rates are calculated using equation (4) and (5).

❖ Aggregate Application Rate:

The aggregate application rate is determined by the following equation

$$C = 46.8\ (1\text{-}0.4\ V)\ H\ G\ E \quad (4)$$

Where,

- C = Aggregate application rate, lbs/SY
- V = Voids in the loose aggregate, in percent expressed
- H = Average least dimension, inches
- G = Bulk specific gravity of the aggregate
- Wastage factor for traffic whip-off

❖ Binder Application Rate:

The binder application rate is determined as follows:

$$B = \frac{2.244HTV+S+A}{R} \quad (5)$$

Where,

- B = Binder application rate, gal/SY
- H = Average least dimension, inches
- T = Traffic correction factor (based on vehicles per day)
- V = Voids in loose aggregate (% decimal)
- S = Surface condition factor, gal/SY (based on existing surface)
- A = Aggregate absorption factor, gal/SY
- R = Residual asphalt content of binder (% decimal)

2.2.2. Australian Design Method

Chip seals (termed as Spray Seals in Australia) are an important component in the road system in Australia. Chip seals are very popular in Australia. The Australian road system comprises some 810 000 km of roads, of which 330 000 km are surfaced with sprayed seals, asphalt, or concrete. Sprayed seals account for around 70% of the total length of all surfaced roads (Austroads, 2006)**.** With the increase of sealed road network, Australia has performed detailed research work on chips seal and has developed a comprehensive design method. Along with time, they have been updating their design method keeping pace with traffic and improvement in materials and equipment. Austroads Provisional Sprayed Seal Design Method – Revision 2000 was initially published which is later followed by the update of Austroads Sprayed Seal Design Method in 2006.

a) Traffic Volume (V/L/D):

Traffic Volume is expressed in vehicles per lane per day, based on average daily traffic. Heavy vehicle traffic is also accounted for by the percentage of equivalent heavy vehicles, EHV. Heavy vehicles are divided into Heavy Vehicles (HV) and Large Heavy Vehicles (LHV), where large heavy vehicles are heavy truck/trailer combinations with seven or more axles. The equivalent heavy vehicle percentage is calculated according to the following equation.

$$EHV\% = HV\% + LHV\% * 3 \qquad (6)$$

Where,

HV% = percentage of heavy vehicles

LHV% = percentage of large heavy vehicles

b) Basic Void Factor, Vf (l/m^2/mm):

The basic Void factor is related to traffic level and is determined from Figures 1 and 2. The central target line is used to determine the Basic Voids Factor in all cases.

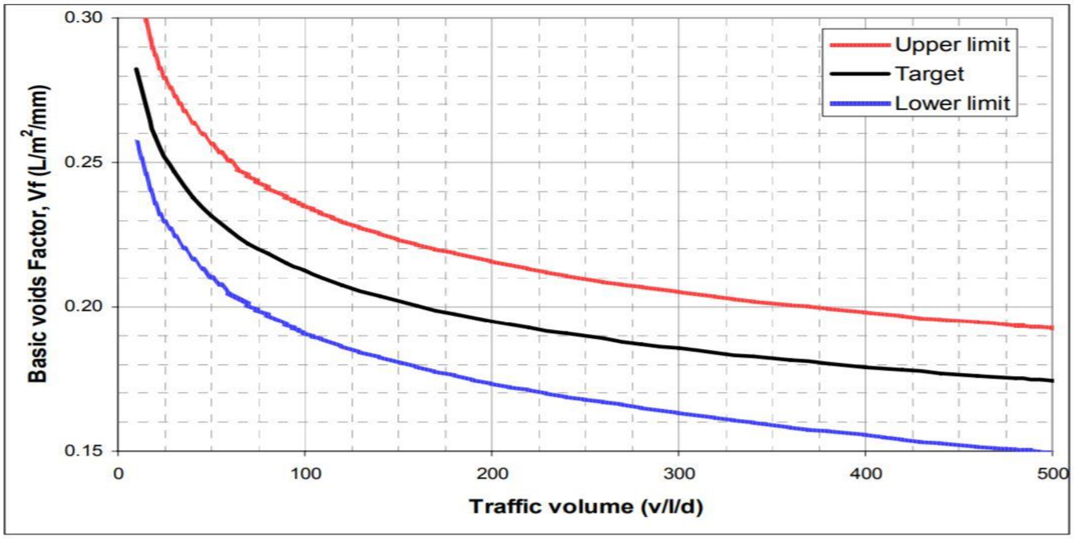

Figure 1. Basic Voids Factor (Vf) - traffic volume 0 to 500 vehicles/lane/day. source (Austroads, 2006)

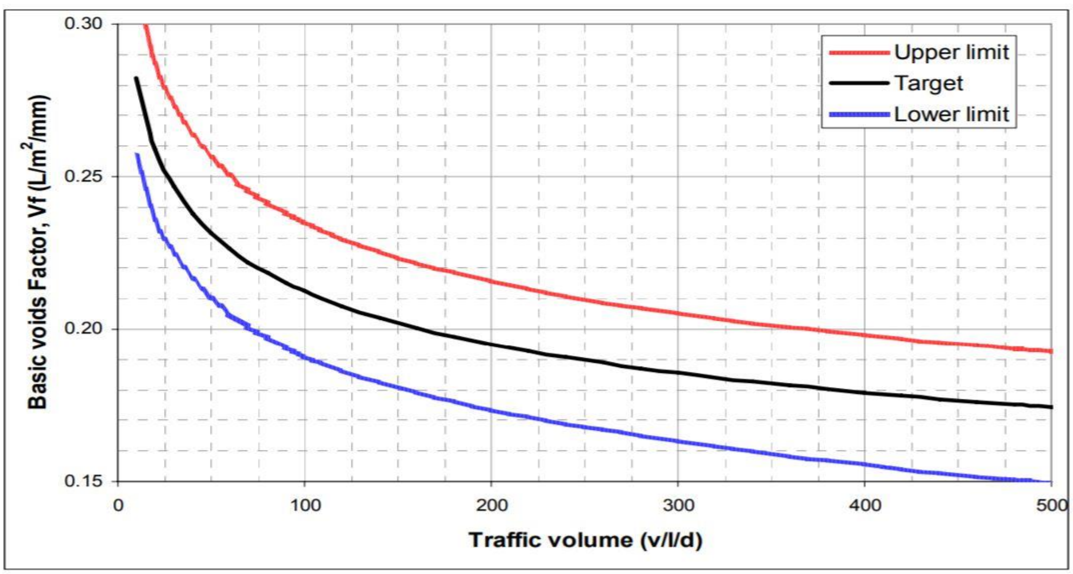

Figure 2. Basic Void Factor (Vf) – traffic volume 500 to 10,000 vehicles/lane/day. Source (Austroads, 2006)

c) Aggregate flakiness index, FI (%):

Same index as used in the McLeod method as seen in equation (1).

d) Adjustments to basic void factor:

Adjustments to the basic void factor are made based on aggregate shape and traffic effects.

e) Adjustment for aggregate shape, Va (l/m2/mm):

Adjustments on the basic void factor for aggregate shape are based on the type of aggregate, its shape, and flakiness index according to Table 3.

Table 3. Adjustment to Basic Void Factor for Aggregate Shape (Va)

Aggregate type	Aggregate shape	Flakiness index	Shape adjustment Va ($L/m^2/mm$)
Crushed or partly crushed	Very flaky	>35	Considered too flaky and not recommended for sealing
	flaky	26 to 35	0 to -0.01
	angular	15 to 25	Nil
	Cubic	<15	+0.01
	Rounded	n.a	0 to +0.01
Not crushed	Rounded	n.a	+0.01

f) Adjustment for traffic effects, Vt (l/m2/mm):

Adjustment for traffic effects is based on equivalent heavy vehicle percentage and the roadway alignment according to Table 4.

Table 4. Adjustment (Vt) to Basic Voids Factor for Traffic Effects

Traffic	Adjustment to Basic Voids Factor (L/m2/mm)			
	Flat or downhill		Slow moving – climbing lanes	
	Normal	Channelised*	Normal	Channelised *
On overtaking lanes of multi-lane rural roads where traffic is mainly cars with ≤10% of HV	+0.01	0.00	n.a.	n.a.
Non-trafficked areas such as shoulders, medians, parking areas	+0.02	n.a.	n.a.	n.a.
0 to 15% Equivalent Heavy Vehicles (EHV)	Nil	-0.01	-0.01	-0.02
16 to 25% Equivalent Heavy Vehicles (EHV)	-0.01	-0.02	-0.02	-0.03
26 to 45% Equivalent Heavy Vehicles (EHV)	-0.02	-0.03	-0.03	-0.04**
> 45% Equivalent Heavy Vehicles (EHV)	-0.03	-0.04**	-0.04**	-0.05**

N/A: Not applicable

*Channelization - a system of controlling traffic by the introduction of an island or islands, or markings on a carriageway to direct traffic into predetermined paths, usually at an intersection or junction. This also applies to approaches to bridges and narrow culverts

**If adjustment for aggregate shape and traffic effects result in a basic void factor of 0.4 $L/m^2/mm$, consider alternative treatments

g) Design Voids Factor (VF):

The Design Voids Factor is calculated as shown below.

$$VF = Vf + Va + Vt \tag{7}$$

Where,

Vf = Basic void factor ($l/m/mm^2$)

Va = Adjustment for aggregate shape ($l/m/mm^2$)

Vt = Adjustment for traffic effects ($l/m^2/mm$)

h) Average least dimension of aggregate, ALD (mm):

Average least dimension of aggregate is calculated by Equation (2).

i) Emulsion Factor (Ef):

Basic binder application rate is multiplied by the emulsion factor before allowances. If bitumen content of emulsion is higher than 67% the emulsion factor is 1.1, otherwise 1.0. This is to compensate for the reduced reorientation of the aggregate due to increased binder stiffness after initial curing in high bitumen content binders.

j) Polymer modified factor, Pf:

The polymer modified factor is selected according to Table 5.

Table 5. Polymer Modified Factor (Austroads, 2006)

Class of PMB	PMB Factor	Type of Treatment
		Aggregate Retention
S10E	1.1	The factors for AR may increased by 0.1 on low traffic applications, but reduced by 0.1 on high to very traffic applications and/or high temperature locations in order to minimize flushing.
S35E	1.1	
		Holding Treatment (HT)
S10E	1.2	The factors for HT may increased by 0.1 on low traffic applications, but reduced by 0.1 on high to very traffic applications and/or high temperature locations in order to minimize flushing.
S35E	1.2	
S45R/S15RF	1.3	
		Weak Pavements (WP)
S20E	1.3	The factors for HT may be increased by 0.1 on low traffic applications where maximum waterproofing is desired and the potential for flushing is low, but reduced by 0.1 on very high traffic volume applications
S45R/S15RF	1.3	
		As a waterproofing seal under OGA (not a SAMI)
S10E, S35E	1.0	Being placed under open graded asphalt, there is little risk of bleeding and the factors should not require further adjustment, although they may be increased, if required, by 0.1 to provide maximum waterproofing.
S45R, S15RF	1.1	
		High Stress Seal (HSS)
S10E, S35E	1.0	Generally, these factors should not be adjusted. They may be reduced, if required, by 0.1 on very high traffic applications and/or hot to very hot locations to minimize flushing or binder pick-up.
S20E, S45R, S15RF	1.1	
M500/170	1.1	
		Strain Alleviating Membrane (SAM)
S10E	1.2	The SAMI factors are designed to provide the maximum practicable binder application rate to optimize resistance to reflective cracking and to waterproof the pavement. They may be reduced, if required, by 0.1 on very high traffic applications and/or hot to very hot locations to minimize flushing or binder pick-up.
S20E	1.3	
S35E	1.2	
S45R, S15RF	1.4	
		Strain Alleviating Membrane Interlayer (SAM)
S25E	1.6	The SAMI factors are designed to optimize the resistance to reflective cracking under Dense Graded Asphalt. The factors may be increased by as much as 0.5 when the SAMI is designed to minimize reflective cracking under Open Graded Asphalt.
S55R, S20RF	1.8	

k) Basic binder application rate, Bb (l/m2):

The basic binder application rate is calculated with the following equation:

$$Bb = Vf * ALD * Ef * Pf \quad (8)$$

Where,

Vf = design void factor ($l/m/mm^2$)

ALD = average least dimension of aggregate (mm)

Ef = emulsion factor

Pf = polymer factor

l) Surface texture allowances (l/m^2):

Binder application rate is adjusted according to the existing surface's texture. The Austroads Sprayed Seal Design Method report states that "Texture measurements should be taken at least every 400 to 500 m or where there is a visual change in texture, such as a change to a seal of different aggregate size." Texture depth measurements are done with a sand patch method where a certain area of the existing surface of the roadway is spread with sand. The volume of sand that fills the surface voids determines the surface texture (Gransberg & James, 2005).

m) Design binder application rate (l/m2):

Design binder application rate is calculated by Equation (9).

$$Bd = \frac{Bb+As+Ae+Ap+Aa}{R} \quad (9)$$

Where,

Bb = basic binder application rate (l/m2)

As = surface texture allowance (l/m2)

Ae = embedment allowance (l/m2)

Ap = binder absorption by pavement (l/m2)

Aa = binder absorption by aggregate (l/m2)

R = residual content of binder (% decimal)

n) Aggregate application rate (m2/m3)

Aggregate application rate for asphalt emulsions is calculated according to Tables 6 - 8, depending on aggregate sizes and the binder type.

Table 6. Aggregate Spread Rate for Sizes>10mm with emulsions

Application		Aggregate spread rate (m^2/m^3)	
		Traffic<200 v/l/d	Traffic>200 v/l/d
Single layer of aggregate		750/ALD	700/ALD
Layer of large aggregate plus scatter coat of 7mm or smaller	First Layer	800/ALD	750/ALD
	Scatter Layer	400-600	400-600

Table 7. Aggregate Spread Rate for Sizes < 7mm with emulsions

Seal Type	Number of aggregate thickness	Rate (m^2/m^3)
Seal/Reseal	1	260-290
	>1	200-250
Scatter Coat (choke seal)	1	400-600

Table 8. Aggregate Spread Rates for Polymer Modified Binders

Traffic conditions	Aggregate spread rate (m^2/m^3)
Traffic<300 v/l/d	750 / ALD
Traffic>300 v/l/d	800 / ALD

2.3. Related Studies and Publications

2.3.1. Concept of Pavement Preventive Maintenance Treatment

Pavement preventive maintenance is a technique that has the potential for both quality improvement and expenditure reduction for a pavement network. The AASHTO definition of Pavement Preventive maintenance is a "planned strategy of cost-effective treatments to an existing roadway system and its appurtenances that preserves the system, retards future deterioration, and maintains or improves the functional condition of the system (without increasing the structural capacity)" (Hicks et al., 2000). Pavement maintenance and rehabilitation activities constitute a significant portion of the budget of state highway agencies in the United States. The road network, which has not significantly expanded since 1960 is now carrying over four times the number of vehicles. Therefore, increased pavement loading with time causes different distresses in pavement. And such distress in pavements not only affects traffic safety but also cost billions of dollars in vehicle repair and operating expenses (FHWA, 2003). According to the World bank's pavement deterioration model, the amount of money required to restore existing deteriorated pavements to their initial state costs four times more than using preventative construction methods (Wilde, 2014). Therefore, pavement treatment before road deterioration is vital from both finance and safety perspectives.

The need for more funding to keep roads in good serviceability has increased rapidly with the ever-increasing traffic loads. Highway agencies have been focusing on preserving highway investment through research and field investigation. Therefore, in order to maximize the advantages of pavement operation with limited funds, the concept of preventive maintenance was introduced. "Applying the right treatment to the right road at the right time as requested by Federal Highway Administration (FHWA), the key is to apply these treatments when the pavement surface is still in good condition with no structural damage in order to prevent higher damage rates and extend the service life of the pavement (FHWA, 2003)**.** The crucial aspect of preventive maintenance treatment is the proper timing of the application of surface treatments. If applied to the pavement surface at their best condition will not only extend the service life of the pavement but also retard the surface deterioration.

2.3.2. Chips seal Performance Evaluation Studies

Chip seal is used worldwide and is very popular due to its ability to provide better performance at the lowest cost. Gransberg and his researchers used a quantitative measurement for the first time in Texas using TNZ P/17 performance criterion to measure one year's texture depth performance. The result showed that poor substrate conditions would adversely affect the performance of a new seal coat (Gransberg, 2008). Hence, the existing pavement condition is a crucial factor to consider before applying the treatment onto the pavement. Labi and Sinha (2004) evaluated the effectiveness of seal coating by using performance jump and deterioration rate reduction (DRR) as an effectiveness indicator. It was found that DRR did not only depends on the pretreatment condition but also depended on the type of treatment. Similarly, Mamlouk and Dosa (2014) verified the effectiveness of chip seals by utilizing life extension, relative benefit, and benefit-cost ratio as indicators. They developed a pavement performance model with exponential regression. They concluded their study with a result which showed that chip seals achieve the highest life extension when the initial pavement condition is smooth.

Liu, Hossain, and Miller (2009) used data from the Kansas Department of Transportation (DOT) pavement management system (PMS) to develop chip seal performance prediction models using linear regression. Performance prediction models were developed for IRI and various other surface distresses as a function of pavement condition after one year of the treatment, traffic levels, equivalent single axle load (ESAL), and highway class (interstate, U.S. highways, and state highways). It was found that their models for transverse and fatigue cracking were not encouraging, more variables were needed for better prediction.

Traffic can play a crucial role in the success of surface treatment, and special design consideration is necessary especially with high average daily traffic (ADT). Bolander (2005) summarized the expected longevity of various seal coat treatments as a function of traffic. Roadways with average daily traffic (ADT) under 100 vehicles per day had expected service life up to 15 years, while the range of expected lives was significantly reduced for ADTs between 100 and 500 Vehicles per day. Moreover, in the past years, chip seals have evolved into maintenance treatment that can work both on low and high traffic volume roads. There is still a controversy in the US whether chip seals can be used effectively on high-volume roads. One of the studies done in Texas concluded that "if rutting is not a concern, chip seals are the best choice for a high traffic area"(Chen et al., 2003). Also, the Nation Cooperative Highway Research Program (NCHRP) synthesis 342 (2005): chip seal best practices found that chip seals have been successfully used on interstate highways with traffic volumes that exceed 100,000 vehicles per day (NCHRP, 2005). Several researchers have shown that chip seals can be used in high traffic volume areas with the use of new techniques such as emulsion breaking agents and the sandwich seal treatment (Chen et al., 2003).

Seal coat performance varies under different climate conditions. It is well known that seal coat treatment in different places cannot have the same effectiveness in performance improvement. The impact of climate on chip seal performance cannot be disregarded (Wielinski et al., 2011; Karasahin et al., 2016). High temperature increases the potential of bleeding and flushing of the asphalt through aggregate. Chip seals in winter conditions are subjected to freeze-thaw cycles and physical damage from snow and ice removal operations. Climate has an important effect on the formation of reflection cracks and longitudinal cracks on pavements. Seal coat construction during or shortly after precipitation can cause the treatment to fail. Also, wind can speed up the curing process as well as distort spray patterns which may cause the non-uniform application. As seal coat performance depends on the evaporation in an emulsion for developing the desired adhesive characteristics; a warmer ambient air temperature results in better adhesion between binder and aggregates and also between chip seal and pavement surface (Gransberg, 2005).

Previous studies showed different deterministic models have been used for pavement performance modeling and is generated by using regression analysis procedures. Colorado DOT designed a model that could predict five different types of distress and smoothness. Non-linear functions are used to fit distress data and the remaining service life is estimated through extrapolation (Colorado DOT, 2012). Virginia Dot developed a model employing IRI as the pavement smoothness parameter using load and non-load related distress indices (LDR, NDR) to characterize the pavement condition. LDR and NDR values are assigned to several types of distresses and those indexes become the response variable where surface age is the only predictor variable in the model (Virginia DOT, 2007). Similarly, different performance models were developed in Louisiana based on pavement types and functional classes. Preservation treatments modeled were chip seals, 2-inch overlays, and microsurfacing. Model forms evaluated were polynomial, exponential, and logarithmic with the general power form, but the only predictor variable is the surface age. Pavement conditions being predicted were IRI, rutting, various cracks, and patching (Khattak et al., 2009). It has been known that the longevity of pavement maintenance treatment depends on various factors such as pavement types, layer thickness, subgrade types, climate, traffic, pavement age, etc. However, not all of the factors have been used as a predictor variable.

Generally, more researches attempt to evaluate the effectiveness of chip seals applied to the pavement with different materials, structures, and exposed to various environment and traffic conditions. The result of this study will help to investigate how potential factors quantitatively influence their effectiveness and to design a better model with the appropriate variables. The performance of chip seals is sensitive to traffic variations (heavy traffic), aggregate characteristics (size, shape, and wear characteristics), and to surface conditions. It is also influenced by weather and binder properties. Some of these effects are only visible after a long period of service. Hence, detailed analysis of a large number of field data over a lengthy period will help us to understand the working and deterioration process of the treatment.

3. DATA SYNTHESIS AND ANALYSIS

3.1. Data Extraction

The field data from LTPP and Austroads are used in this study to achieve the objective of evaluating the effectiveness of chip seals treatment. In 1980s, the transportation research board (TRB) initiated the Long-Term Pavement Performance (LTPP) program. The LTPP database is the central database funded by the federal highway administration (FHWA) to collect and analyze pavement data in the United States and Canada. The scope of LTPP program is large enough to assess the long-term performance of pavements under various loading and environmental conditions over a pavement’s life. Basically, it's not only about evaluating the existing design method rather, its objective is to determine the effects of loading, environment, material properties, variability, construction quality, and maintenance levels on pavement distress and performance along with an aim to provide improved design methods and strategies, design equations for rehabilitation of existing, new and reconstructed pavements. The LTPP program collects the data from in-service roads, which consist over 2500 test sections throughout North America. LTPP database has been designed in an efficient way such that users can easily get access to the data present in different modules such as inventory, Maintenance, Monitoring (distress, deflection, and profile), rehabilitation, materials testing, traffic, and climate.

Furthermore, the data are categorized into two different fundamental classes of study: general pavement studies (GPS) and specific pavement studies (SPS). General pavement studies are restricted to pavements that incorporate materials and designs representing good engineering practices and that have strategic future importance while SPS programs are a study of specially constructed, maintained, or rehabilitated pavement sections incorporating a controlled set of experiment design and construction features. These studies are further divided into 10 SPS studies categories based on construction treatments, pavement structure, types of materials. However, SPS-3 studies are preferred for this research which focuses on the effectiveness of various maintenance treatments on pavement service life. And among the various maintenance treatments such as crack seal, slurry seal, and asphalt overlay, chip seal treatments are the main focus of this study.

LTPP Section Details:

The pavement sections from nine different states treated with chip seals located in Washington, Utah, Idaho, South Dakota, Montana, Wyoming, Texas, Mississippi, and Florida have been chosen for this study. Moreover, there are very few seal coats treated sections recorded in the database. Among those sections, some have insufficient performance data (cracking, rutting, and roughness) and data also not available for a required time period. Therefore, data from different states are combined together to evaluate the change in performance along with time. These sections from different states are selected due to their availability of the data and mainly to see the performance of treatment in two different regions. As the pavement sections are from north and south regions, their performance may vary according to the weather. Hence the comparison will also provide some valuable insight into the performance of treatment in two different regions. The data extracted from the LTPP are listed below.

- performance data: Alligator cracking, longitudinal cracking (wheel-path & non-wheel path), transverse cracking, longitudinal profile (International roughness index), transverse profile (rutting).
- Pavement structure and construction data: General section information (experiment type and improvement (M&R) history, original pavement surface construction dates), pavement layer type and thickness (representative pavement structure), material-layer properties and field sampling (asphalt concrete aggregate and binder), maintenance and rehabilitation (asphalt seal coat projects details, improvement details).
- Traffic data: Annual traffic inputs over time (annual average daily truck traffic & annual average daily traffic).
- Climate data: Precipitation and temperature

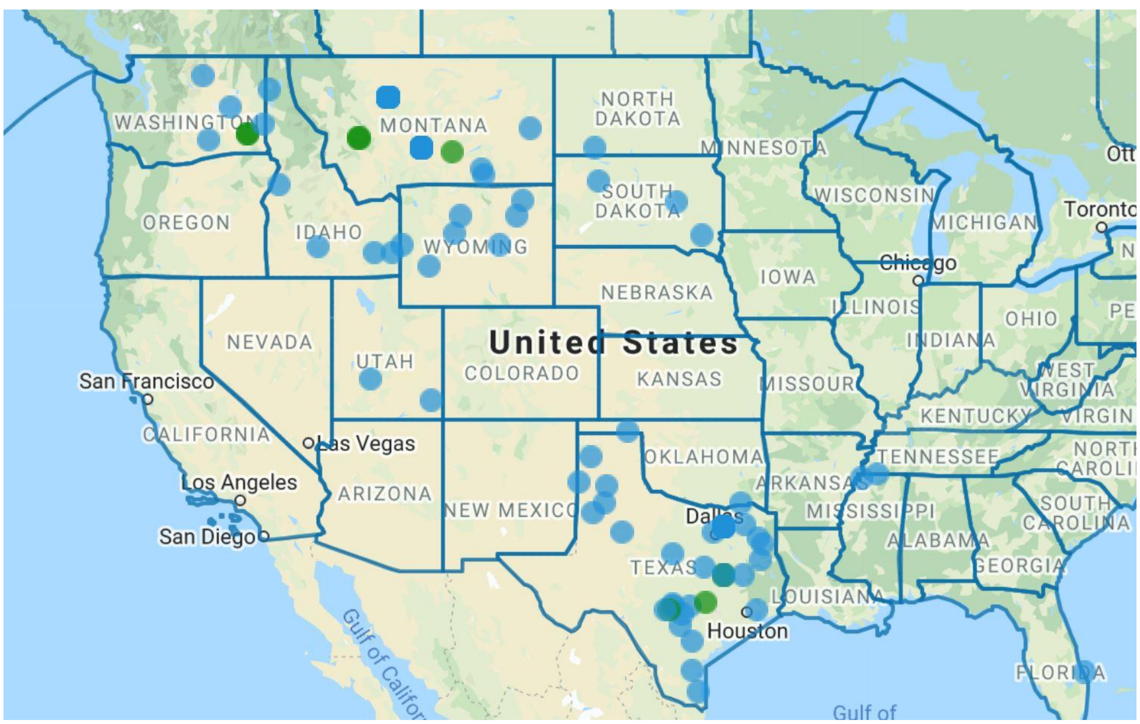

Figure 3. Chip Seals Treated Sections in the United States. Source: (LTPP Infopave™ Database)

Figure 3 shows the number of pavement sections selected for this study. The sections are spread out towards the north and south regions. The sections are asphalt pavement with 152 m (500 ft) length. The summary of the information regarding the pavement sections located in different states are provided in Table 9.

Table 9. Pavement Sections Details

State	Average Annual Temperature (°C)	Average Annual Precipitation (mm)	Range of Average Annual Truck Traffic (AADTT)	Maximum Aggregate Size Used (mm)
Utah	10.85	217.55	160 to 238	12.7
Wyoming	6.8	342.6	45 to 330	12.7
Washington	10.6	377.183	17 to 182	12.7
Idaho	8.3	473.92	90 to 452	12.7,9.525
South Dakota	8.225	560.425	11 to 170	12.7, 9.525
Texas	19.37	873.95	31 to 923	19.05,15.875,12.7
Montana	7.7	379.7	5 to 680	9.525
Florida	23.5	1383.475	916 to 1586	12.7
Mississippi	16.5	1429	20 to 25	12.7

Table 9 shows summarized information of the pavement sections that are located in nine different states. The above information illustrates the average temperature, precipitation, the maximum aggregate size used, and truck traffic range in specific states. The most common types of binders used in the northern part are high float asphalt emulsion, polymer modified asphalt emulsion, cationic rapid setting emulsion and in southern regions are paving grade asphalt cement, asphalt emulsion.

3.2. Data Analysis:

Five common distress are chosen as the performance evaluator of chips seals treatment for this study. The performance change is assessed in terms of major distresses: roughness, rutting, alligator cracking, longitudinal (wheel-path & Non-wheel-path) cracking, and transverse cracking. Change in distress over the eight-year period is examined after the application of chip seals treatment. Those measurements are compared with the performance before the treatment for all five distresses. This was done to find out whether chip seals are successful in reducing the distresses or not and further to see how long it can work effectively before severe concerns are observed on the pavement. Though various measures are taken while applying the treatment to get better performance, some pavement shows good performance, while some show poor performance after a certain period of time. This contrast in the treatment's effectiveness is influenced by many variables such as construction and design, existing pavement condition, weather, age, traffic, materials, and pavement structure. For this study, the variable used is regions (North and South), climate zone, existing pavement condition (good, fair & poor), seal coat thickness, pavement surface, pavement age at the time of application of the treatment, annual average daily truck traffic, temperature, and precipitation. The size of aggregates, binder application rate, aggregate application rate, and seal cure time is also used in the study. But due to lots of missing data, they are not employed to perform any statistical tests, which would produce biased estimates leading to invalid conclusions.

The performance data are grouped into six categories: performance after few months, one-year after, 2 to 3 years after, 4 to 5 years after, 6 to 8 years after, and performance before applying the treatment. This grouping of data into several time-period helps to notice even small changes occurring over time that will provide some meaningful information to the research. Not all the distress data in this study have measurements recorded for eight years. Also, some of the pavement sections have received various treatments during the eight years, and if included, those sections would affect the performance evaluation process. Hence, these obstacles are overcome by removing those pavement sections from the analysis. The statistical procedure was carried out using R-studio (Version 1.3.1073). Data is well structured, and any missing data present in the dataset are removed from the study. Then, the first step in the analysis is to check the distribution of the data, which is performed by using the Shapiro-Wilk test. The null hypothesis of this test is that the sample distribution is normal. If the test is significant, the distribution is not normal. An assessment of data distribution is a prerequisite before data analysis and for performing many statistical tests. For example, normally distributed data is an underlying assumption in parametric testing. In this study, the normality test showed that the data are not normally distributed. The p-value of the test is lower than the significance level (α=0.05). Even though the data is slightly different from a normal distribution, a statistical test is further performed to measure the skewness and kurtosis in the data. Skewness is a measure of symmetry or the lack of symmetry in the dataset. Similarly, kurtosis is a measure of heavy-tailed or light tailed to a normal distribution. From the test, the data is positively skewed with acceptable values (1.11, 1.365). The results are acceptable otherwise there lies a bigger problem in the data.

Since the Shapiro-test result showed that the data does not hold normality assumption, a non-parametric (one-way ANOVA on ranks) test such as the Kruskal-wallis H test is used to determine if there are statistically significant differences between two or more groups of an independent variable on a continuous dependent variable (rutting, roughness, cracking). After the test is run for all the dependent variables on different groups where a significant difference in all samples is observed, those groups are further subjected to another test to find the differences among different groups levels and find out which levels are significant. Pairwise tests for multiple comparisons of different levels of groups are performed using Dunn's test. However, the statistical difference observed from Dunn's test is sometimes affected by the correlation between different sets of data. That's why it is equally important to find out the relationship among these variables and how much related are each variable. However, the correlation test will only provide the relationship whether it is a positive or negative relation between these variables. But the test will not provide any information about the slope of the line. And this could be achieved by using a parametric test such as linear models. But the normality test result proved that data is not normal. The first thing is to go through the assumptions of normality; the most needed thing is that the data must have a normal distribution, and it should have homogeneity of variances and a linear relationship. Simple linear regression and multiple linear regression are the best methods to investigate the relationship between two or more explanatory or independent variables and a dependent variable by fitting a linear equation to observed data. Every value of the response variable (independent variable) is associated with the value of the dependent variable. Multiple linear regression takes into account all specified variables at the same time. The model is used to study how the independent variable changes with the dependent variable. The regression parameter (β), coefficient of determination (R^2), and test static (p-values) were utilized to compare the effect of all the independent variables on these distresses (Brieman & Friedman, 1997). The equation that represents the multiple linear regression is:

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \ldots\ldots \beta_i X_i \tag{10}$$

Where Y = dependent variable (Rutting, or MRI, or Cracking(after the treatment)); α = intercept; β_1, β_2, β_3 = slope and X_1, X_2, X_3 = independent variable (e.g. change in distress before the treatment, Pavement age, AADTT, Precipitation, Temperature).

In order to use a linear model, the transformation of data into normal distribution is must needed. Otherwise, the model that violates the normality assumption would not be meaningful. Therefore, to achieve the normality of data, the data is transformed using Box-Cox power Transformation. Box-Cox power transformation is used to modify the distributional shape of a set of data to be normally distributed so that the tests and confidence limits that require normality can be appropriately used (Osborne, 2010). The Box-Cox transformation has the following mathematical form.

$$Y = (X + \delta)^{\lambda} \tag{11}$$

Where λ = exponent (power); δ = shift amount that is added when X is zero or negative.

The standard λ values of -2,-1.5,-1,-0.5,0,0.5,1,1.5, and 2 are usually investigated to find out which one is the most suitable value for transformation. The optimum value of λ is determined by using maximum likelihood estimation. And the optimum value is adopted using confidence interval limits. The value of λ between the confidence interval is selected for the linear model. After that, the value of λ is used in the linear model to transform the response or dependent variable. Before the transformation, we need to make sure that all the variables included in the linear model must be highly significant.

So, analysis of variance and linear model is employed to see the independent variable's effect on the dependent variable. And if the p-value for the respective independent variable is significant, then that variable is kept for designing the model using transformation. For this study, models for roughness and rutting after one year of the treatment are created. Cracking data is not useful for model design due to many nearly zero values in the data after one year of the treatment. Despite that, some of the variables were excluded from the model because they were strongly correlated with other variables. And if those variables are included, it would reduce the precision of the estimate coefficients and will also weaken the statistical power of regression models. Regression model equation is obtained with r-squared value along with the plots for rutting and roughness.

3.3. LTPP Performance Evaluation

a) Longitudinal Profile (International Roughness Index):

The roughness value is measured in terms of International Roughness Index (IRI). IRI values are measured for both left and right wheel-path. And mean roughness index (MRI) is computed by taking the average value of both wheel-path. The boxplot shows the change in mean roughness index before and after the treatment. Several MRI measurements after the treatment are recorded for a 8-year time period which is further divided in five categories as shown in Figures 4 and 5. To find out if there is any change in roughness over time after the treatment, statistical tests are performed which showed that p-value for the test is greater than the significance level (0.05).

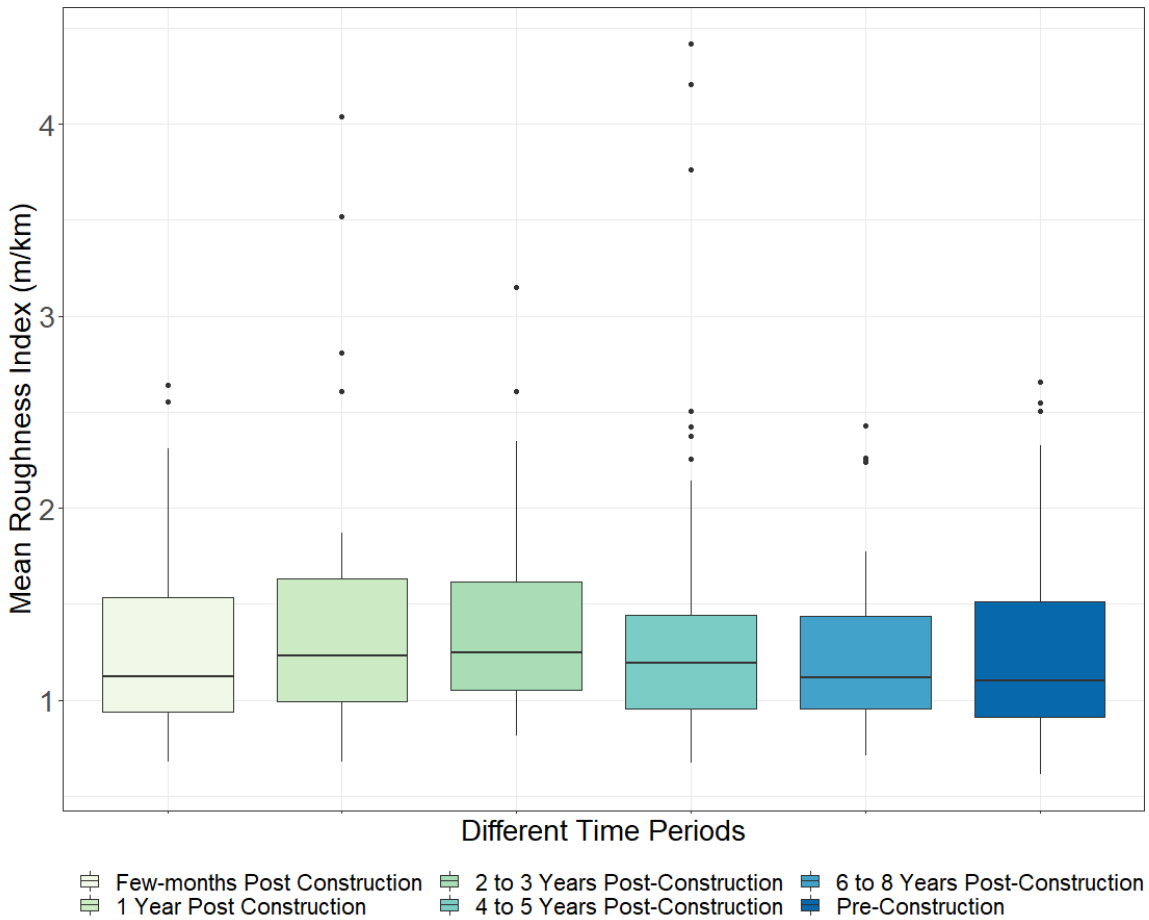

Figure 4. Mean Roughness Index Change with Time

This means that no significant changes in roughness is seen along the time after applying seal coat treatment. From Figure 4, a slight increase is noticed in the 1-year and 2nd to 3rd years after the treatment. And a small amount of reduction in roughness is observed in 4th to 5th years and again remains the same in the 6th to 8th year period after the treatment. Visual inspections are not usually reliable. Therefore, the statistical tests are preferred to get better insights of the data and the test proved that change in roughness is not significant over time.

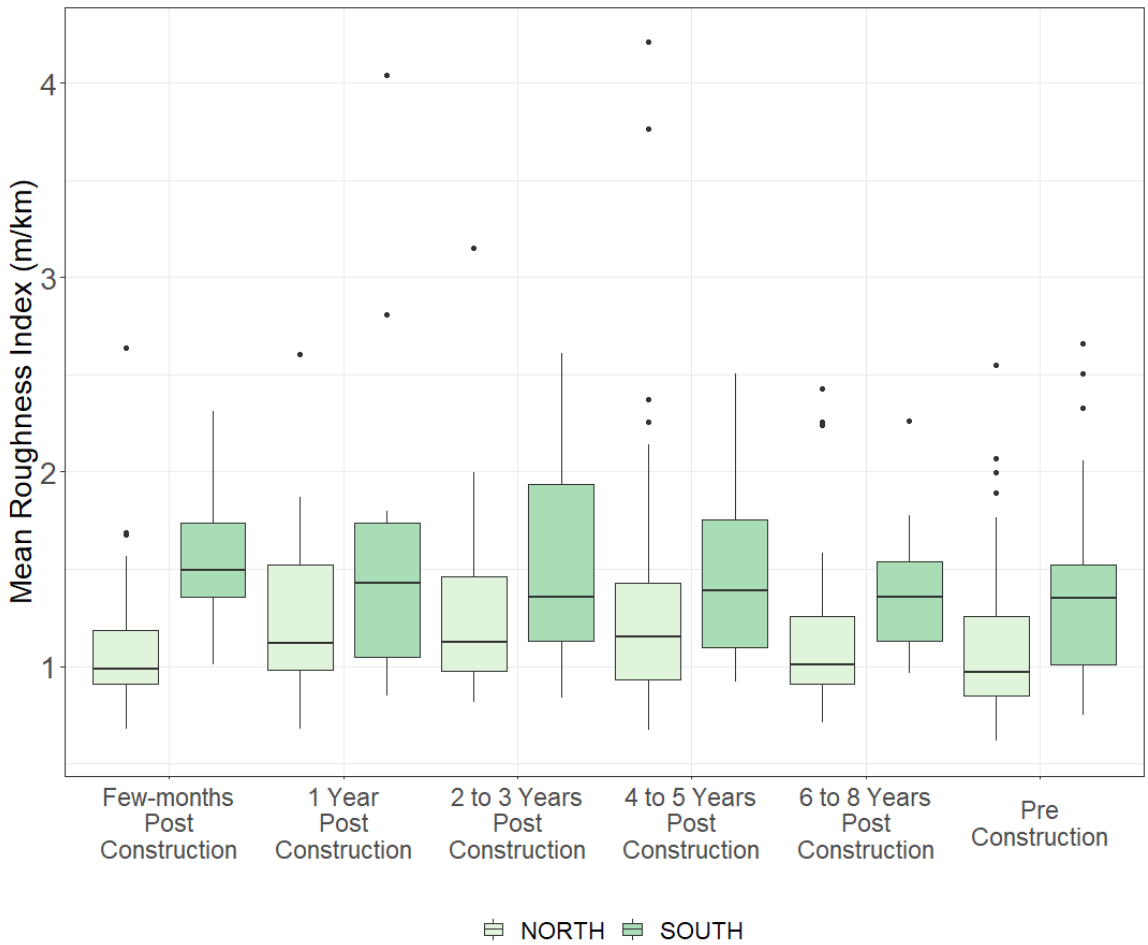

Figure 5. Mean Roughness Index Change with Time in Two Regions (North & South)

The mean roughness change before and after applying chip seal treatment in two different regions over time showed a statistically significant difference ($p<0.05$). Figure 5 clearly shows notable differences in two different regions. Higher MRI values are observed in south when compared to northern regions. But in both regions, the performance change for MRI over time is quite similar. Both regions showed no statistically significant difference over time and even no significant difference before and after the treatment.

Four different climatic regions showed a statistically significant difference in MRI. Wet-freeze zone has a higher roughness. The second higher MRI value is noted in wet no-freeze region whereas dry climatic regions (Dry Freeze & Dry No-Freeze) have shown lower MRI values. Also, a slight increase in MRI is observed in all climatic regions after the treatment as shown in Figure 6. However, it is not statistically significant enough to prove that there is a change in performance before and after the use of seal coat treatments.

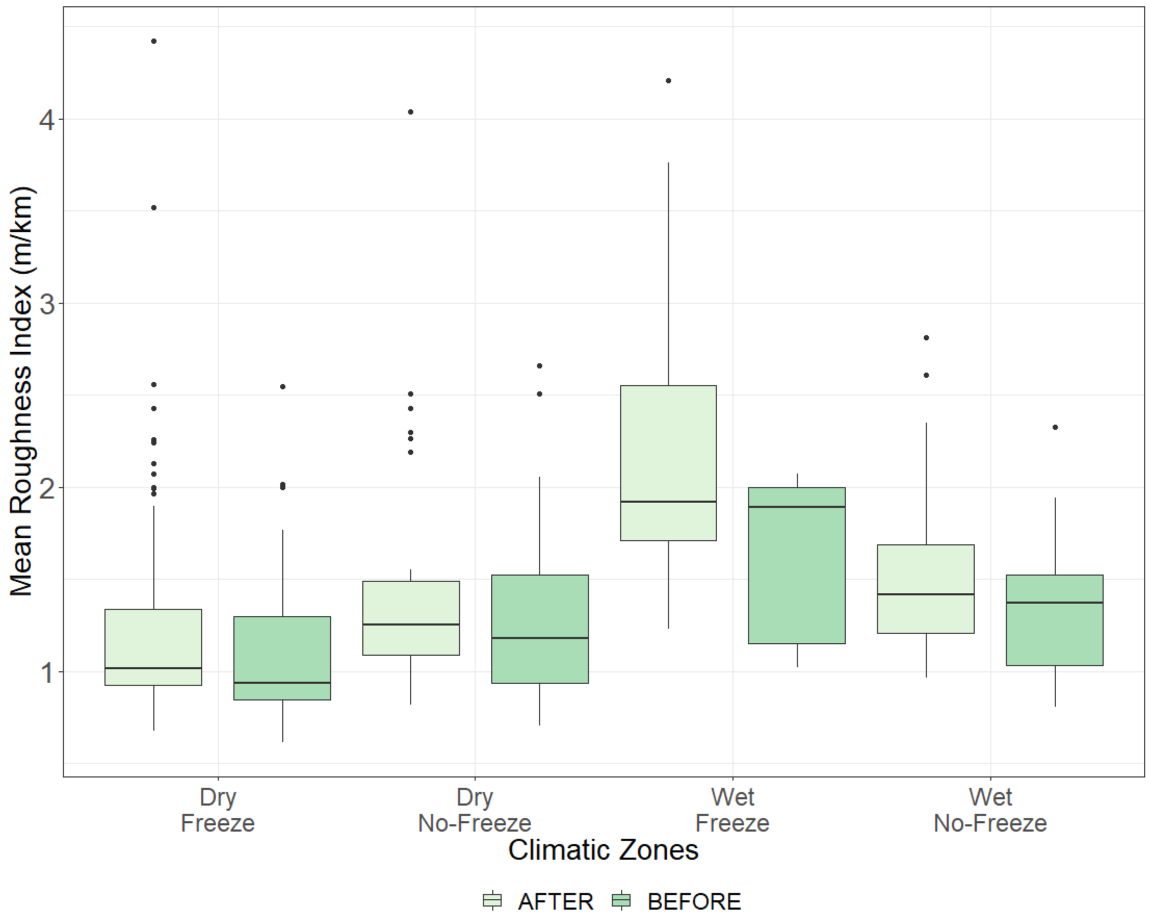

Figure 6. Mean Roughness Index Change in Climatic Zones (Before and After)

The pavement treated by seal coats varies according to the types of existing surface of pavement sections. Some sections have asphalt overlay as a surface layer while some sections have the original surface layer (Hot laid Hot Mixed-Dense graded asphalt layer) that have not been subjected to any maintenance treatment. And some sections have already been treated in the past by seal coats. Therefore, three different pavement surface types showed different roughness performance. Among them, seal coat treatment given to pavement that already has existing seal coat as a surface layer has shown higher roughness than others. Moreover, asphalt overlay and original surface layers show no significant difference in roughness performance. In Figure 7, the median value of roughness has slightly increased in asphalt overlay and original surface layer after the treatment while no change is seen in roughness before and after the treatment for sections that already have seal coat as a surface layer.

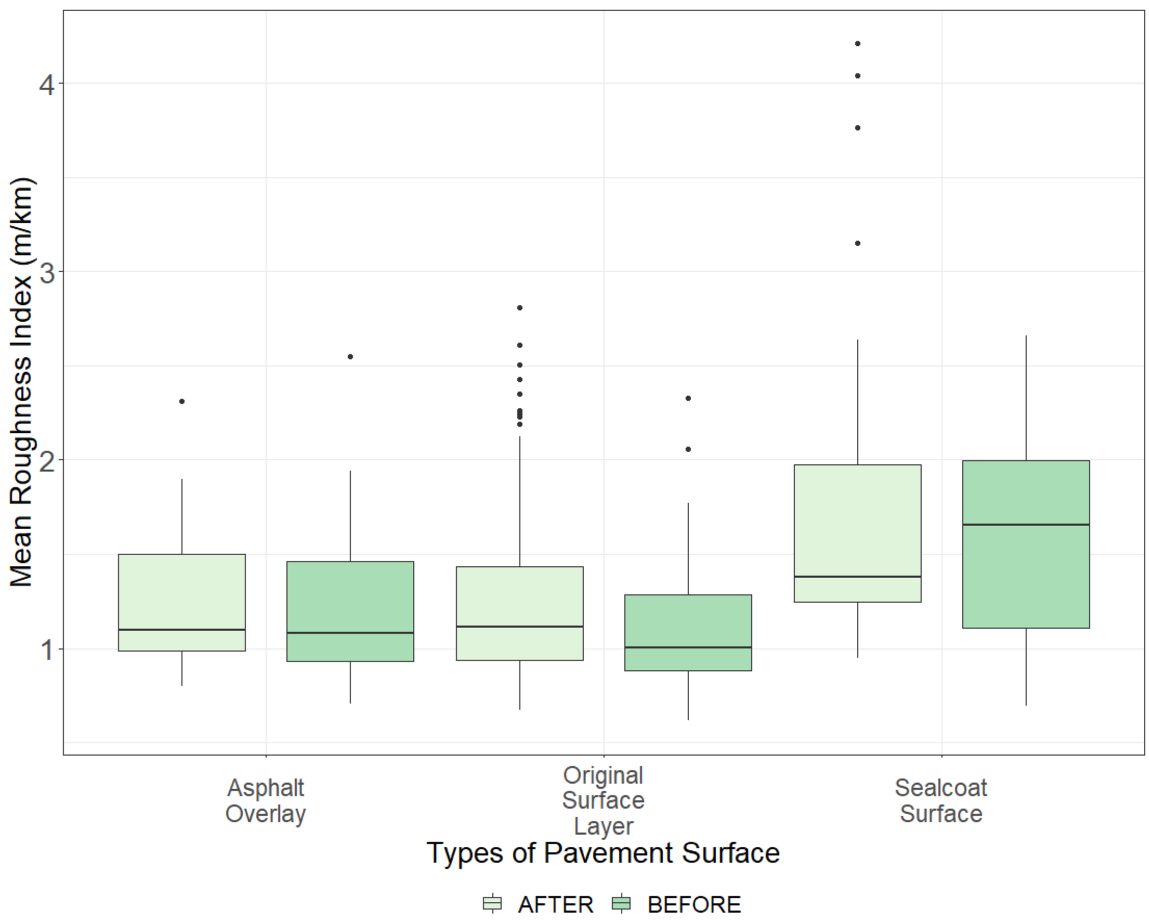

Figure 7. Mean Roughness Index Change in Existing Pavement Surfaces (Before & After)

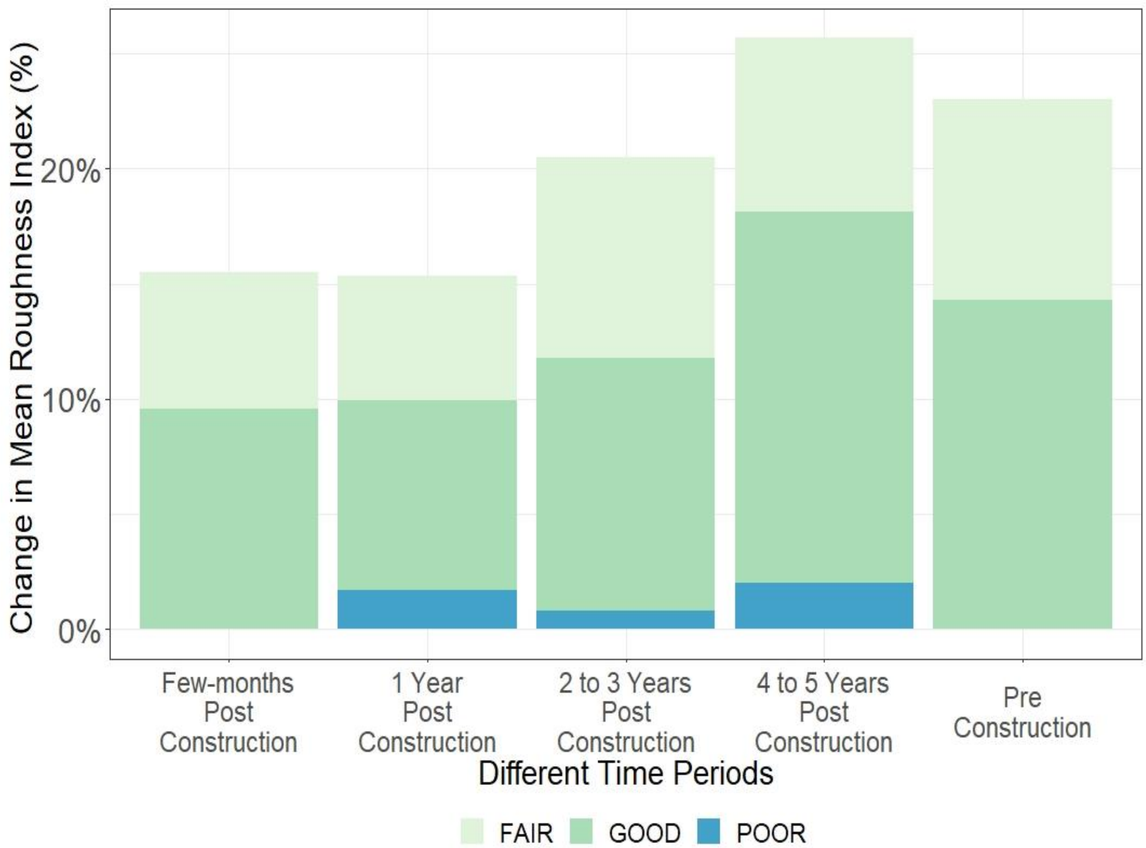

Figure 8. Mean Roughness Index Change with Pavement Condition Index

Pavement existing condition is a major factor to consider before application of chip seals. The threshold which defines the condition of roughness in pavements as good (<1.5), fair (1.5-2.68), and poor (>2.68). Figure 8 showed that chip seals are mostly placed in good and fair pavements. Even after a few months of the treatment, the pavement remained in the same state. But poor roughness condition starts to arise in the first year of the treatment.

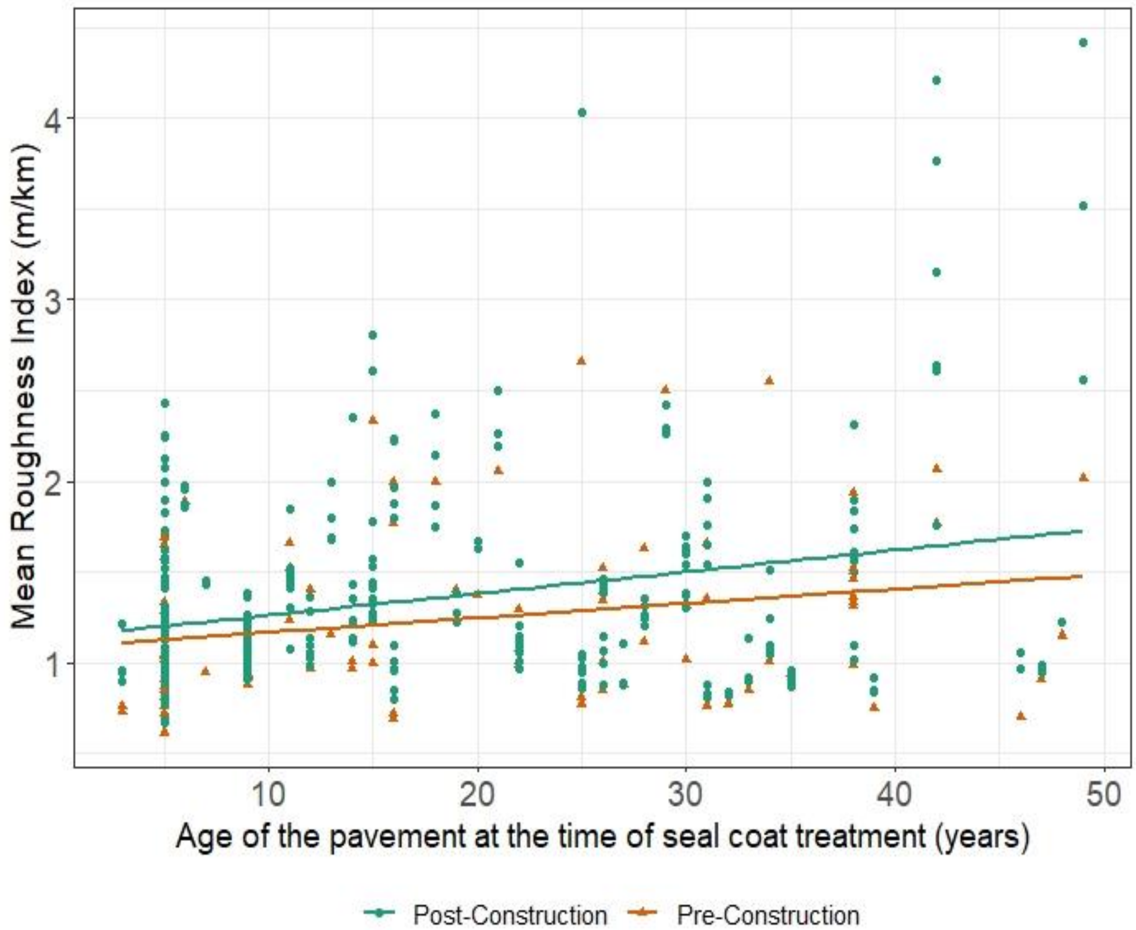

Figure 9. Mean Roughness Index Change with Pavement Age

Pavement age at the time of application of seal coat treatment is also one of the important variables that affect the effectiveness of performance. As shown in Figure 9, mean roughness index increases with pavement age. However, it has increased even after the application of treatment and the increment rate in older pavement is slightly higher than in younger pavements.

b) Alligator Cracking:

Alligator Cracking is a series of interconnected cracks which is measured in terms of area. The cracking data of five-year period is considered for alligator cracking. Most of the pavement sections received various maintenance treatment after five years of chip seals treatment. Hence, 6th to 8th year period data is not taken because it will affect the study and analysis. Chip seals are very effective in reducing minor non-load related cracks. However, alligator cracks have been reduced significantly after the application of seal coat. The crack area is nearly zero in the first few months and 1-year after the construction. But Cracks started to develop in the 2nd and 3rd years, and it starts increasing along with time which is also evident in Figure 11.

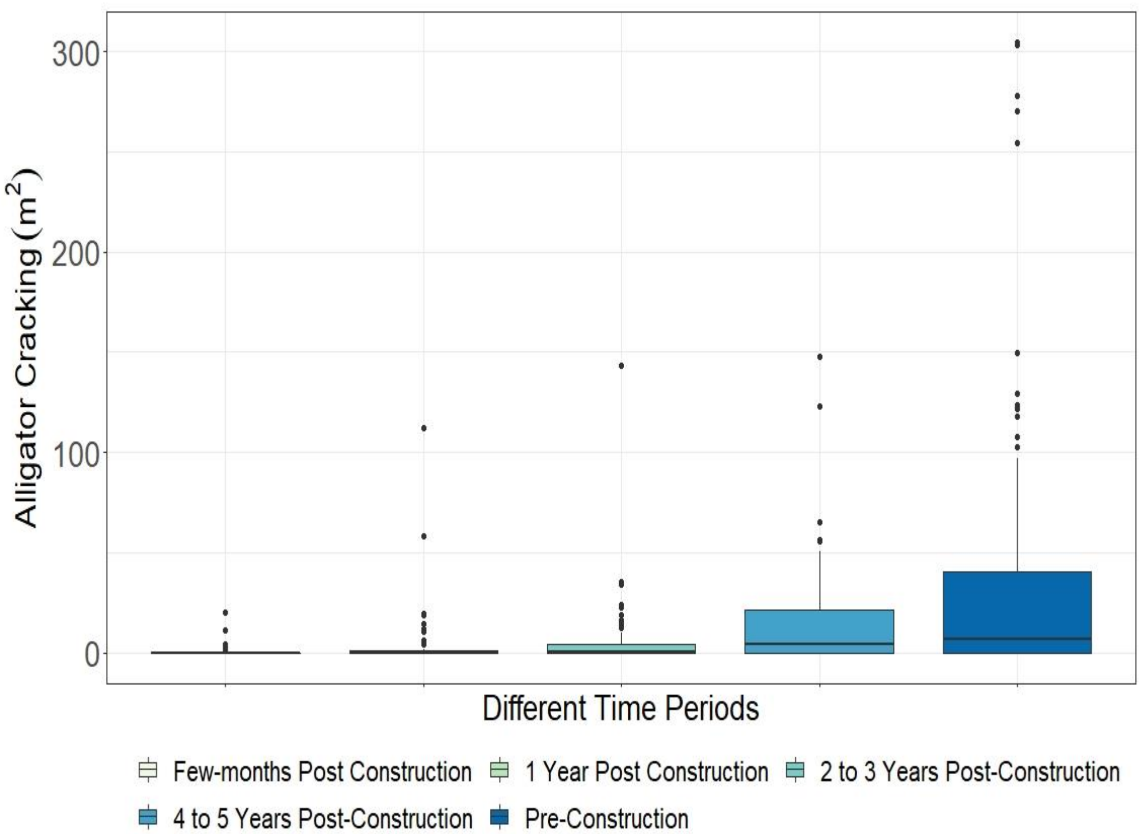

Figure 10. Alligator Cracking Change with Time

The performance of alligator cracks in the different regions along with time is shown in Figure12. Alligator cracks are higher in the north region than in the south. In the north, alligator cracks have increased in the 4th to 5th year of the application of chip seals. Whereas in the south, low alligator cracks are seen in the 5-year period. It is important to point out that sections in the south region have very low cracking even before the treatment. So this could be the reason that very low cracks are seen in south till the 5th year period.

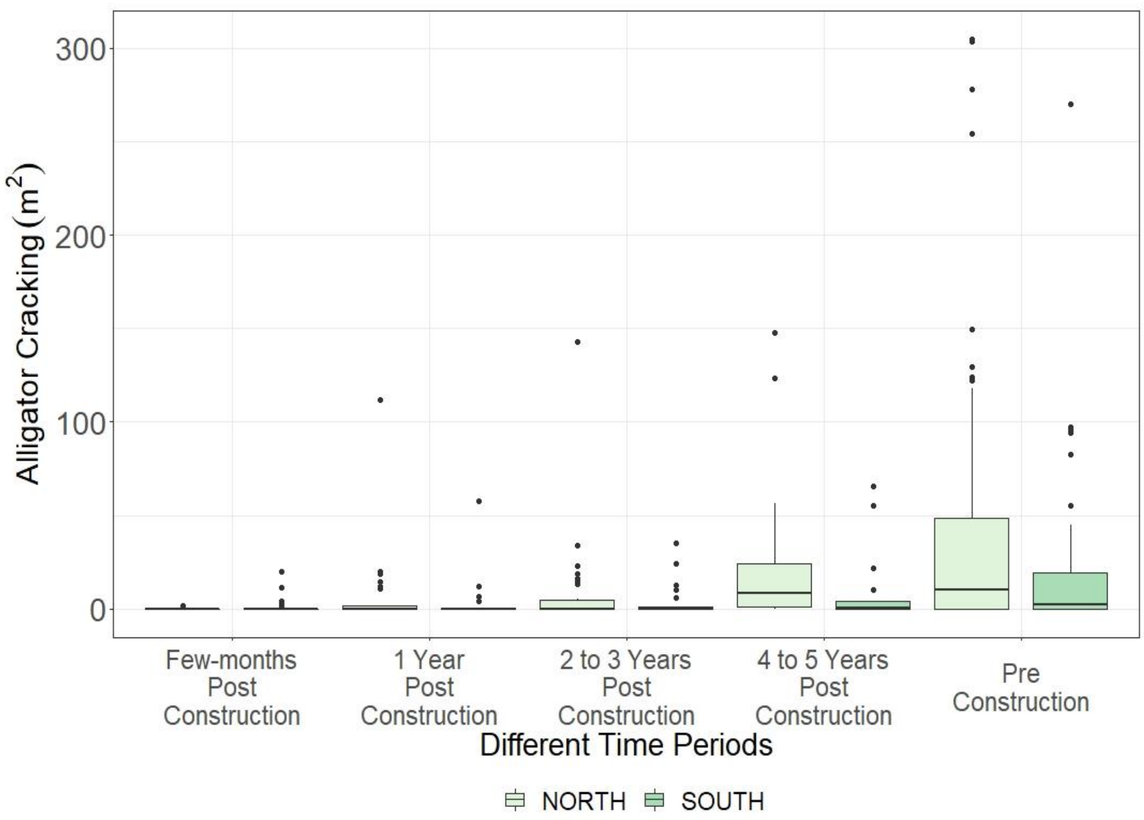

Figure 11. Alligator Cracking Change with Time in Two Regions (North & South)

Further the data is divided into different climatic regions based on location of each pavement section. Pavement sections fall under three different climatic zone for alligator cracking data. A statistical test is employed to compare performance difference in three climatic regions over time. And the result showed performance in dry freeze zone differs from other two regions which is seen in Figure 12. Dry no-freeze and wet no-freeze region showed a reduction in alligator cracks after the treatment, while the cracks present in the pavement before the treatment is also lower in two regions. Alligator crack in dry freeze zone before the treatment is higher than the other two regions.

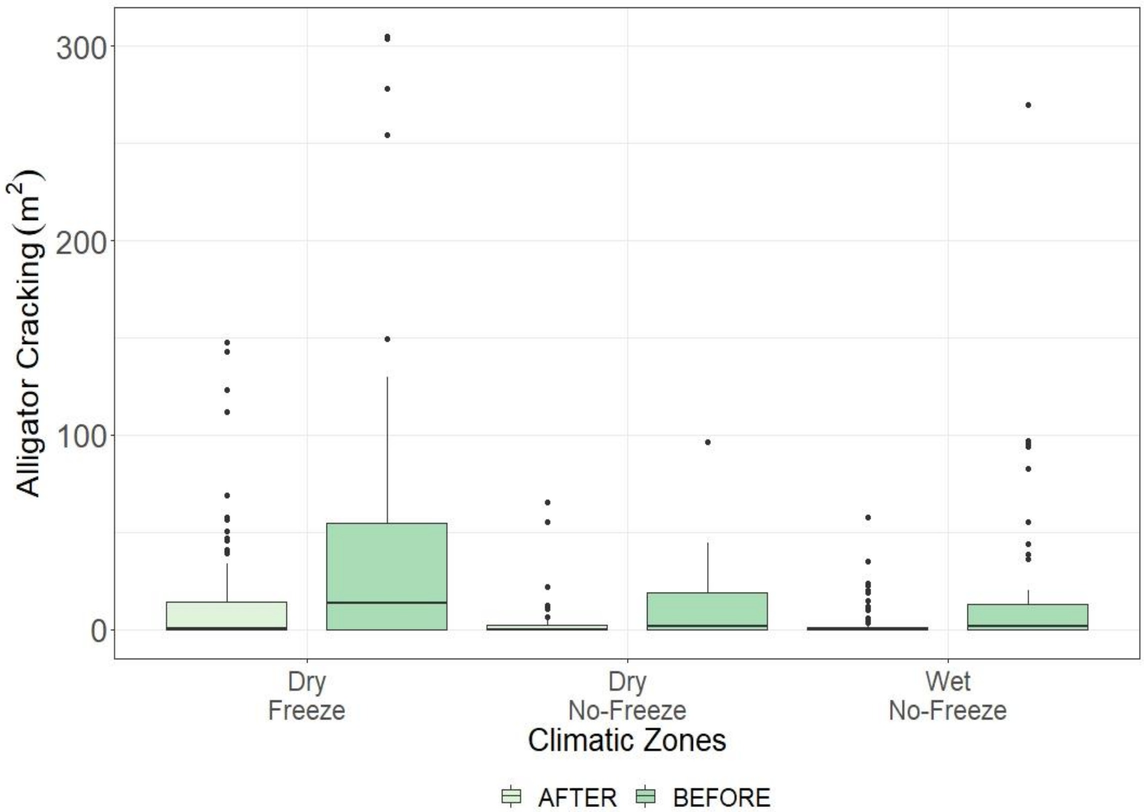

Figure 12. Alligator Cracking Change in Climatic Zones (Before and After)

c) Longitudinal Cracking:

Longitudinal Cracks occur parallel to the centerline of the pavement. They are measured in length. The longitudinal cracks that occur in wheel path (WP) as well as in non-wheel path (NWP) and hence the distresses are measured in both wheelpath. Longitudinal Wheel-path cracks are fatigue-related. From Figure 13, it is clear that these pavement sections have very low longitudinal cracks. And after the application of chip seals, it has been further reduced and the cracks are nearly equal to zero. It appears that the cracks starting to form from the 2nd year and steadily increasing with time.

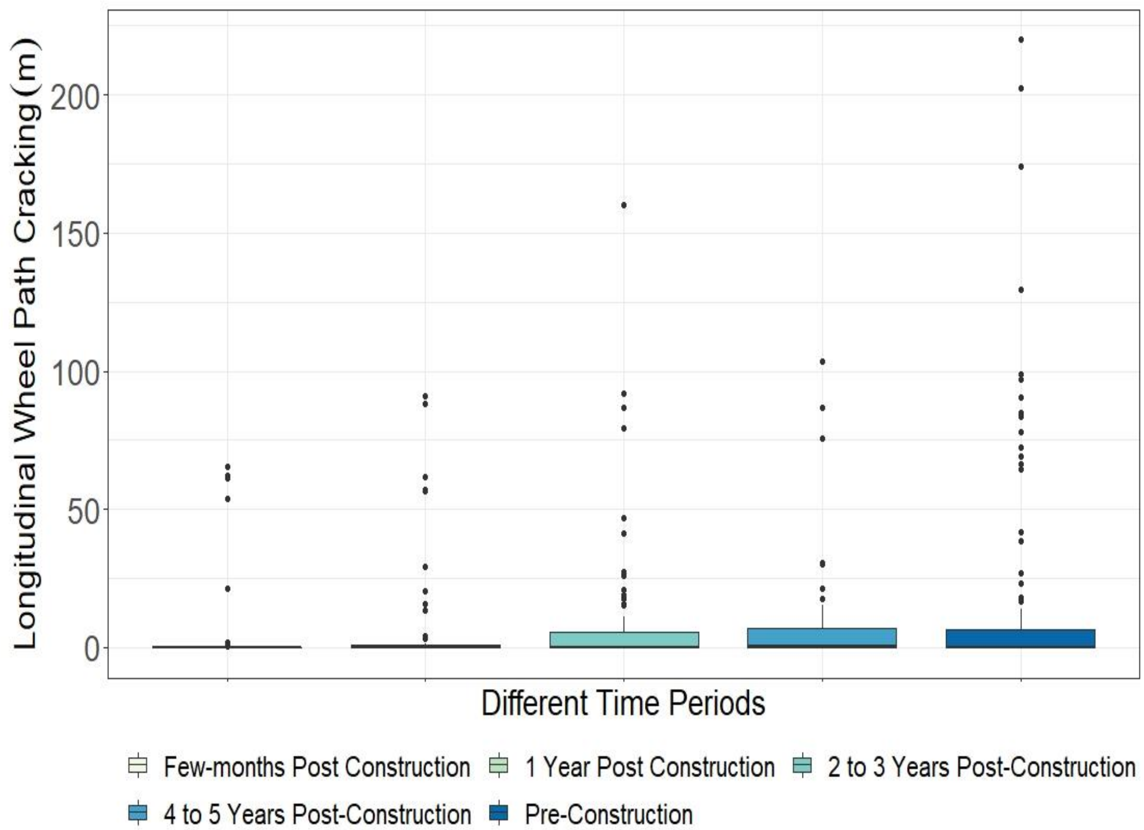

Figure 13. Longitudinal Wheel Path Cracking Change with Time

Longitudinal Non-wheel path Cracks are mainly caused by the factors associated with cracking phenomena such as pavement temperature, asphalt binder and aging, pavement structure, construction issues. The longitudinal cracking for the non-wheel path is comparatively higher before the treatment as shown in Figure 14. But after a few months of construction, the cracks are completely sealed. The cracks started to form after 1st year of the treatment and it kept on increasing every year from then, as shown in Figure 15. In the 4th to 5th year, the longitudinal NWP cracks have increased rapidly.

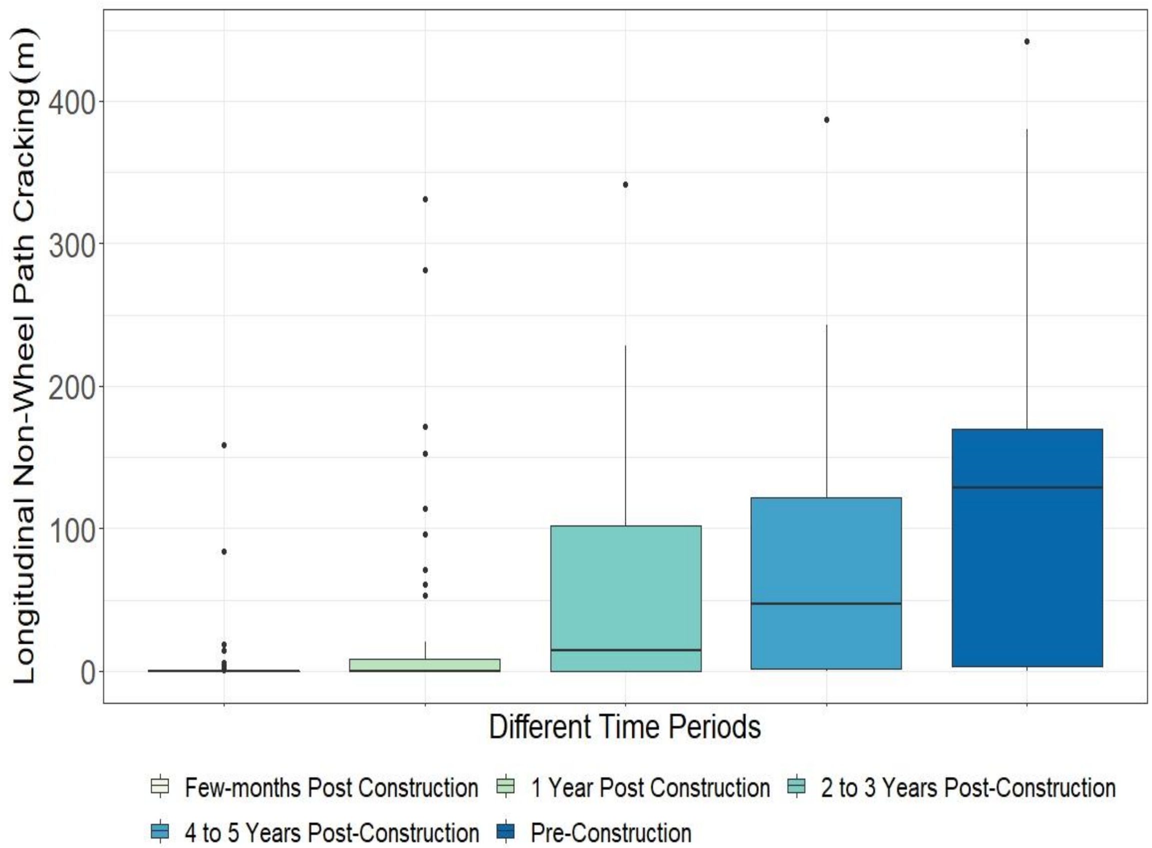

Figure 14. Longitudinal Non-Wheel Path Cracking Change with Time

The difference in the median values of cracks at pre-construction in Figure 15 clearly shows North Region has much higher longitudinal NWP cracking with a higher increasing rate than the south. Seal coat treatment has shown its effectivity in the first few months and the first year after the treatment. The cracks are developing from the 2nd year. However, there is a steady increase in cracks in pavement sections from south whereas north region has a higher increasing rate.

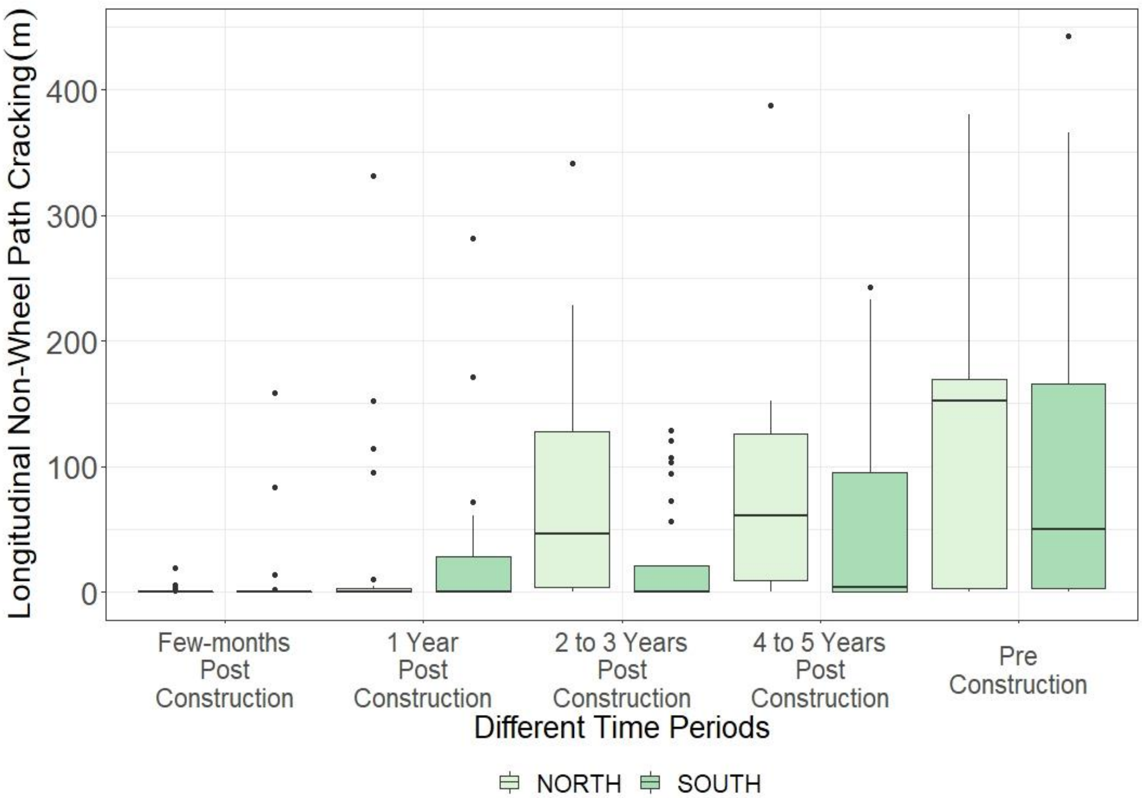

Figure 15. Longitudinal Non-Wheel Path Cracking Change with Time in Two Regions (North & South)

The longitudinal non-wheel Path cracks are more evident in dry-freeze and dry no-freeze zone. It is important to notice that dry freeze zone has higher cracking length before but the amount of cracks have been significantly reduced after treatment. While in dry no-freeze, the cracks are lower when compared to dry freeze. But the reduction in cracks after the treatment is not as much as bigger as the pavement sections in dry freeze shown in Figure 16. Figure 17 shows significant reductions in cracks after the treatment in all three pavement surfaces.

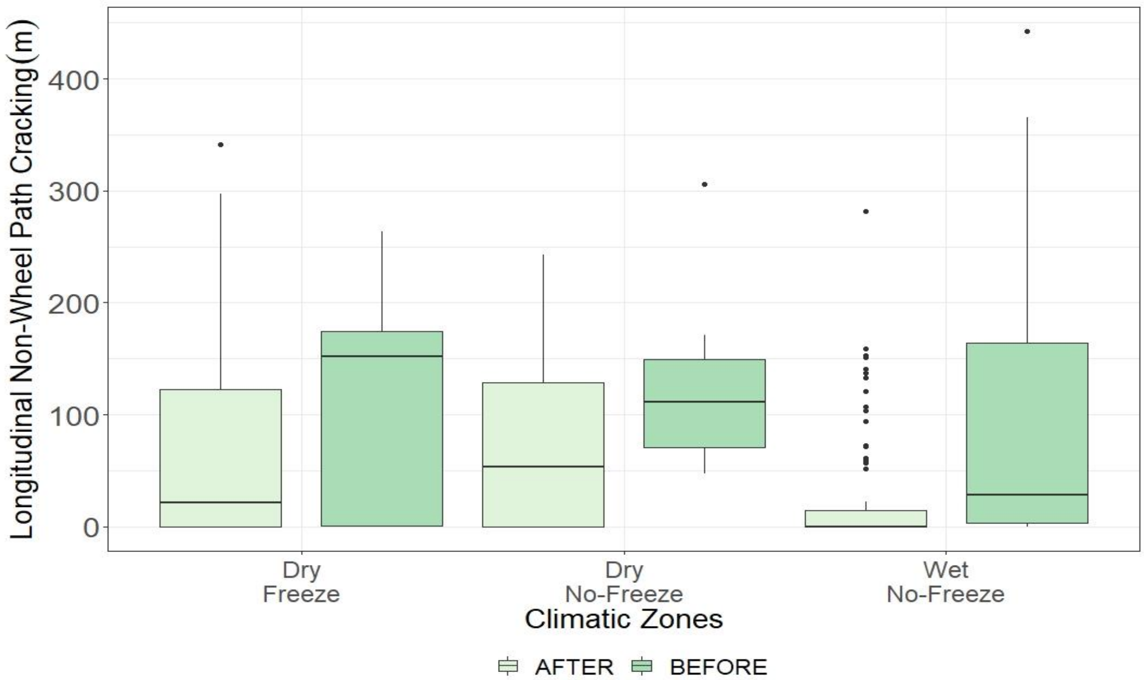

Figure 16. Longitudinal Non-Wheel Path Cracking Change in Climatic Zones (Before & After)

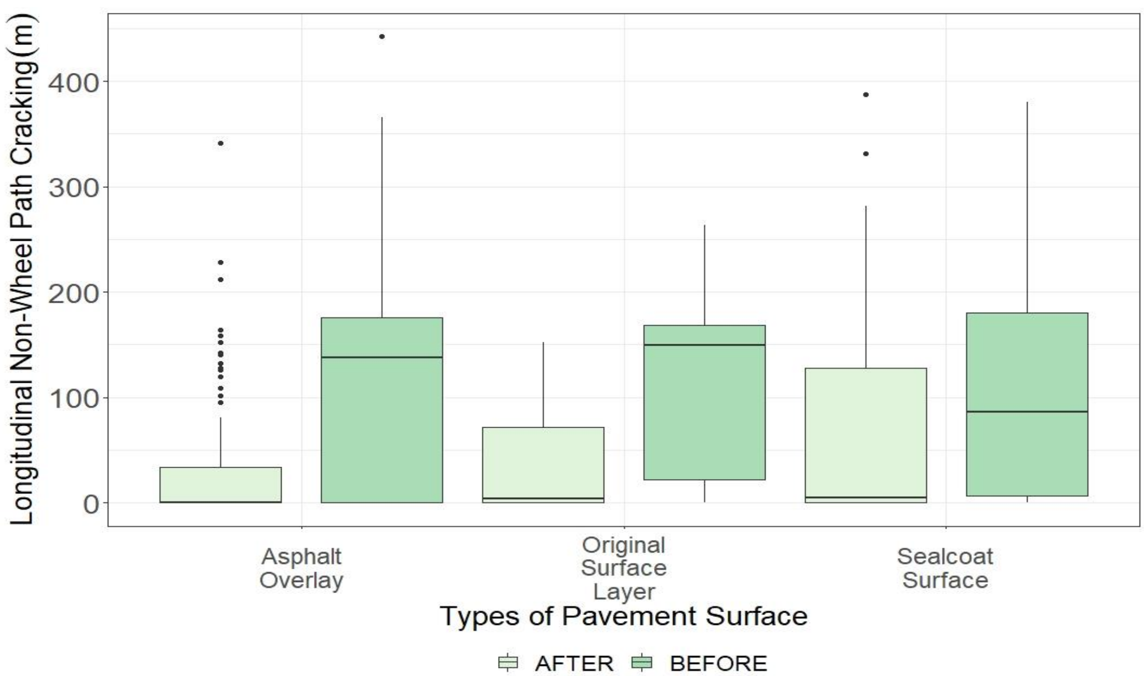

Figure 17. Longitudinal Cracking Change in Existing Pavement Surfaces (Before & After)

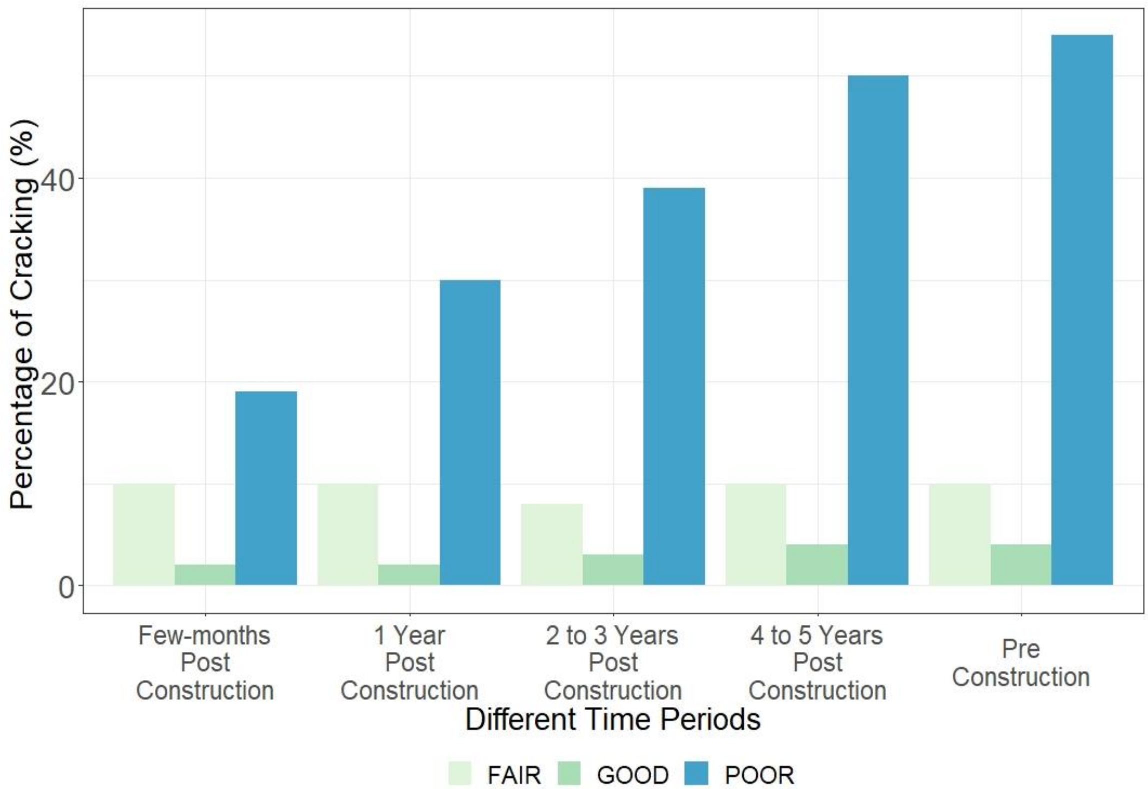

Figure 18. Percentage of Cracking with Time

In Figure 18, the pavement condition threshold is used to quantify the performance in terms of pavement condition index: good, fair, and poor. The pavement sections in good and fair conditions have remained the same over time after the use of treatment. The reduction in crack percentage is seen in poor pavements. The cracks in poor conditions are reduced by almost 35 % just after few months of the treatment, and then the cracks begin to increase from 1st year. Moreover, the deterioration rate is around 10% from the start to fifth-year time period for pavements in poor conditions. Hence, pavement condition before treatment is crucial to performance change after the treatment.

d) Transverse Cracking:

Transverse crack occurs perpendicular to the centerline of the pavement. These types of cracks are non-load related and mainly caused by shrinkage of asphalt layer and asphalt binder hardening or reflection from an existing crack. After the application seal coat, the cracks have been sealed within the first few months of construction. But from the 2nd year, the cracks again begin to form and increasing with time. From Figure 20, it is clearly evident that transverse cracking is higher in northern part than south because these cracks are highly sensitive to low temperatures.

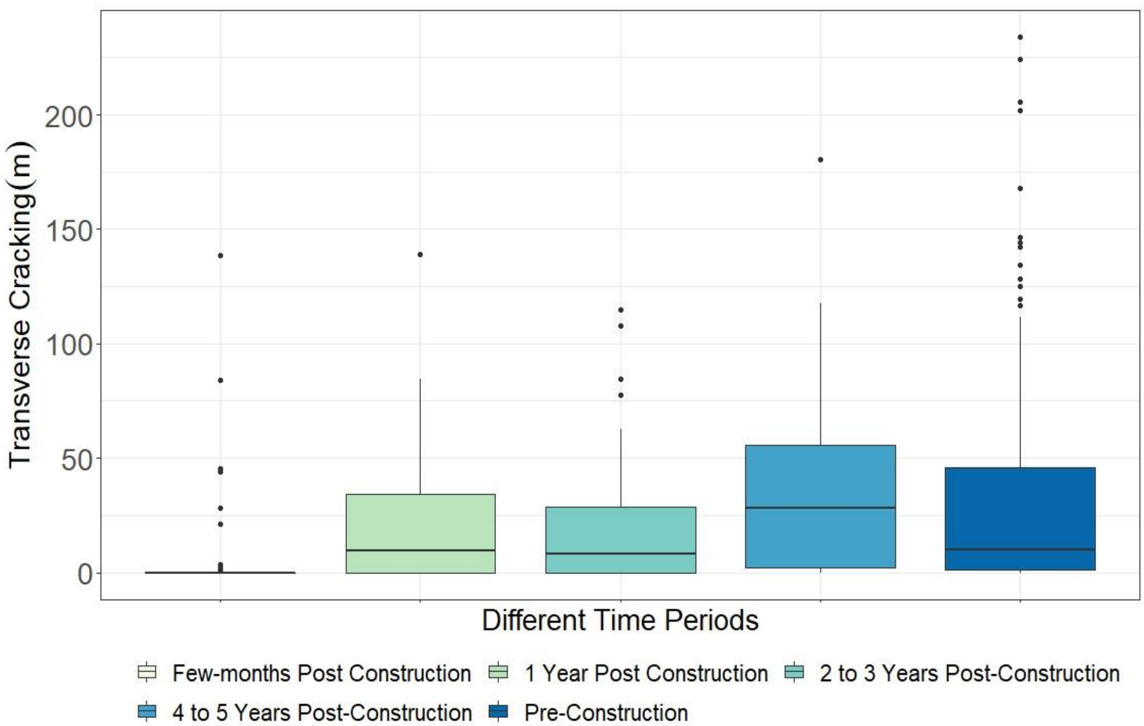

Figure 19. Transverse Cracking Change with Time

Transverse cracks are much observed in northern region. It seems that Seal coat treatment is not as effective in reducing transverse cracks. The performance over time in different regions have not changed much after treatment. Different pavement surfaces showed no change before and after the treatments as seen in Figure 21.

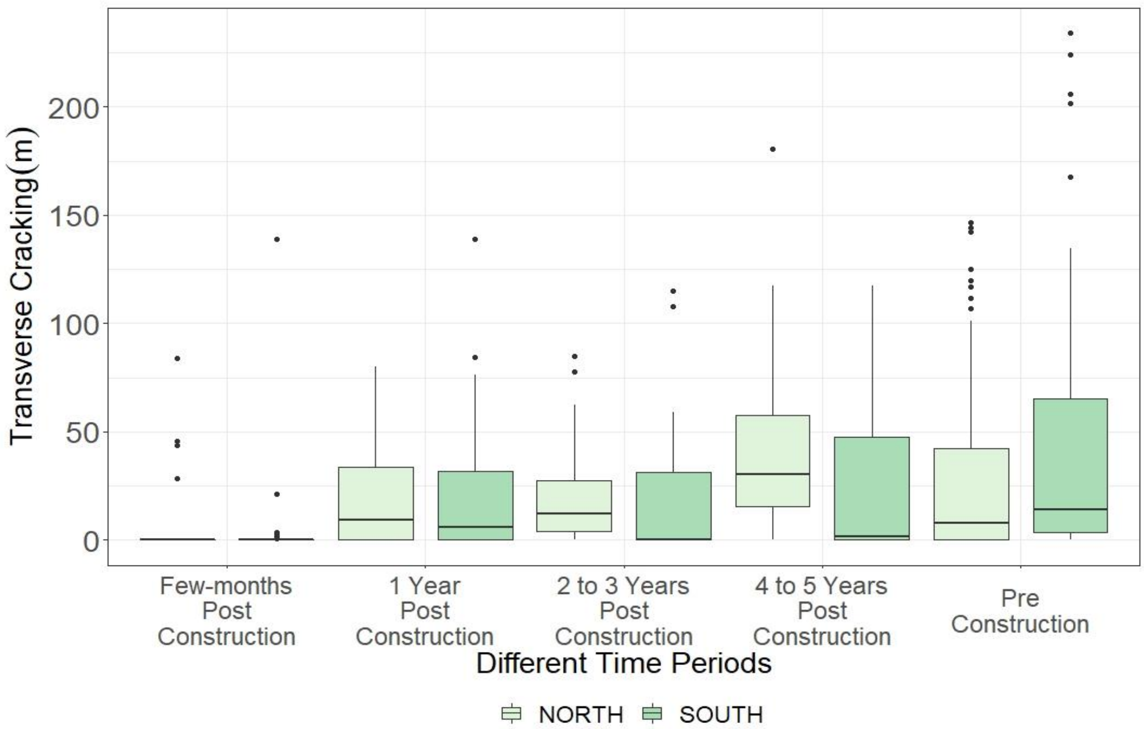

Figure 20. Transverse Cracking Change with Time in Two Regions (North & South)

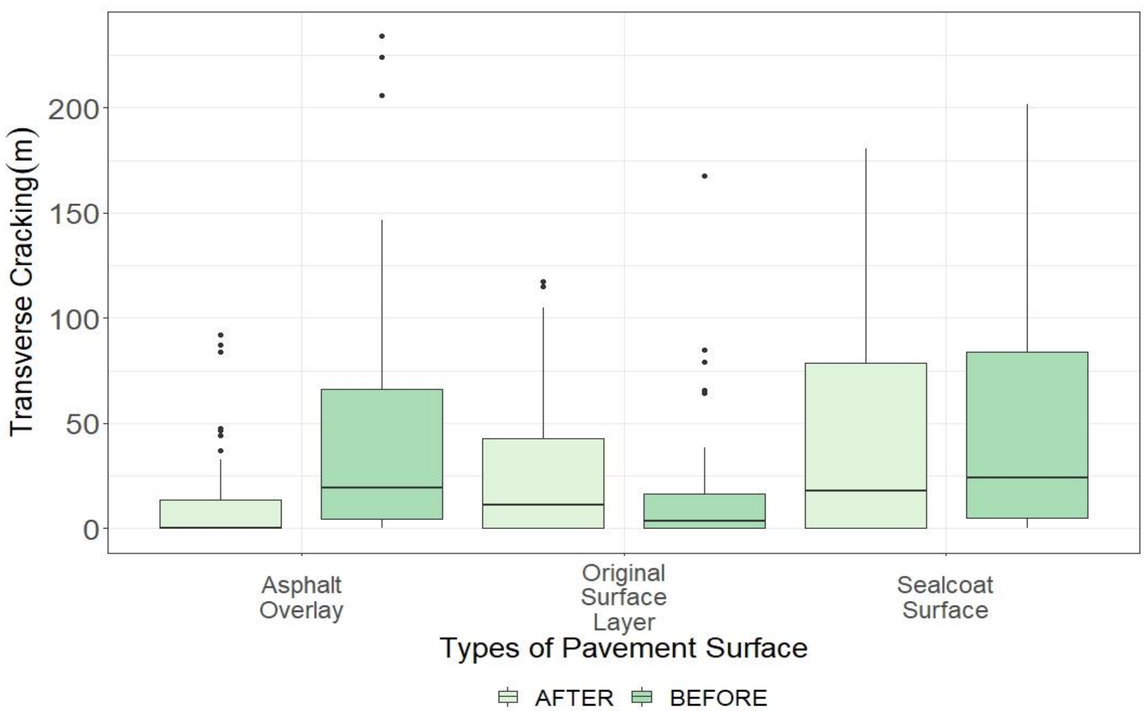

Figure 21. Transverse Cracking Change in Existing Pavement Surfaces (Before & After)

e) Rutting:

Rutting is a permanent deformation in pavement layers or subgrade usually caused by the lateral movement of materials due to traffic loading. Rutting is considered as structural damage to the pavement. seal coat treatments are not suitable to address any structural issues in the pavement. But it is still necessary to carefully observe the performance of rutting over time. Figure 22 shows a minimal increase in rutting throughout the eight-year time periods. The change in rutting is not statistically significant over time.

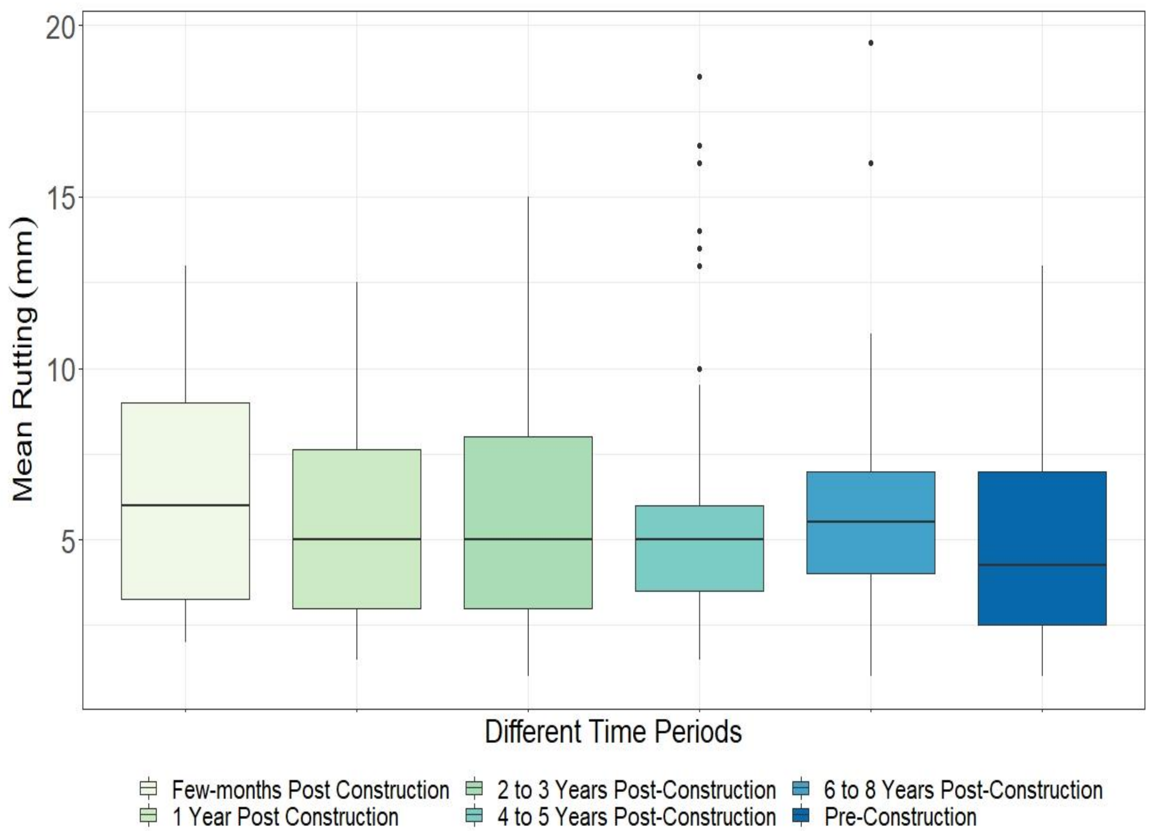

Figure 22. Mean Rutting Change with Time

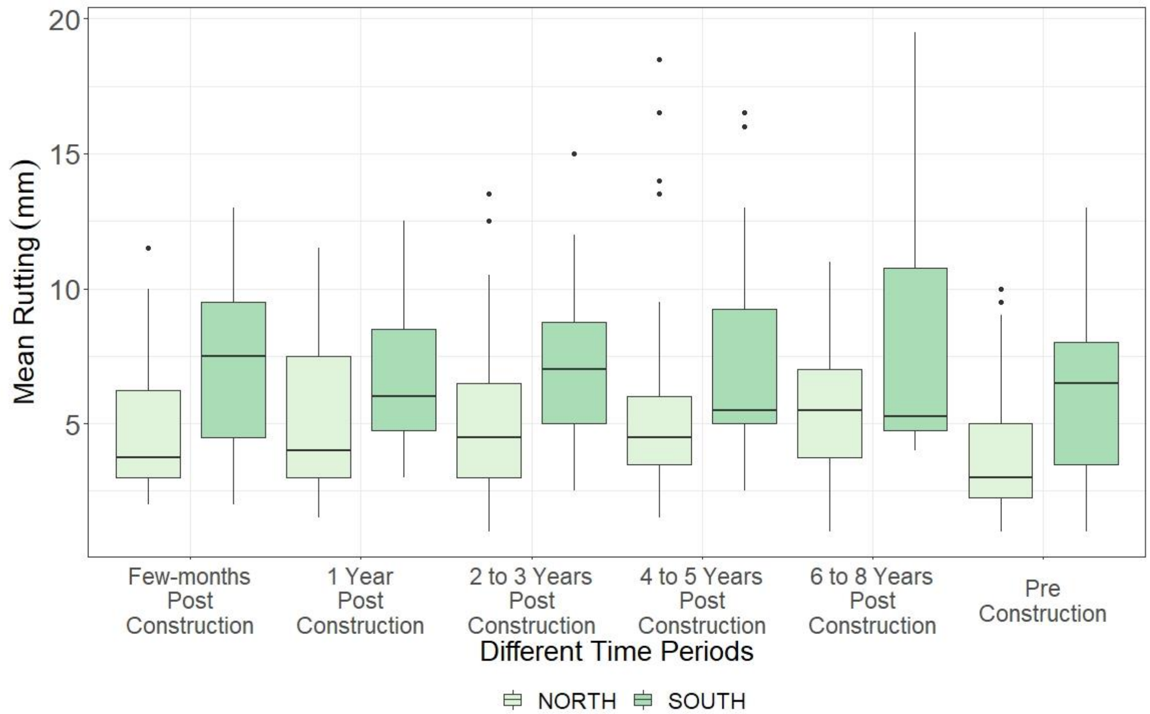

Figure 23. Mean Rutting Change in Two Regions (North & South)

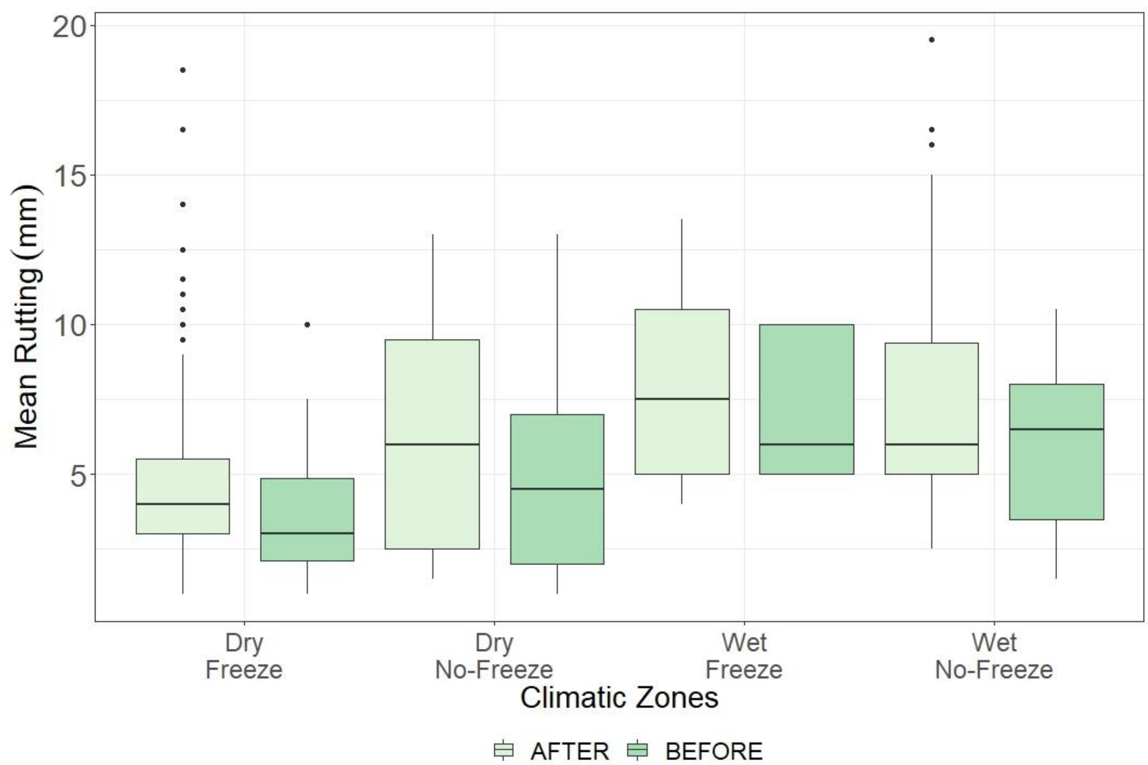

Figure 24. Mean Rutting Change in Climatic Zones (Before & After)

However, two different regions have different rutting performance, and the statistical result shows significant performance differences in the two regions. South regions have very high rutting values compared to the north region as shown in Figure 23. Similar to MRI, higher rutting is spotted in the wet freeze zone compared to other climatic regions. The increase in rutting after the treatment is more elevated in dry no-freeze and wet freeze zone which is seen in Figure 24.

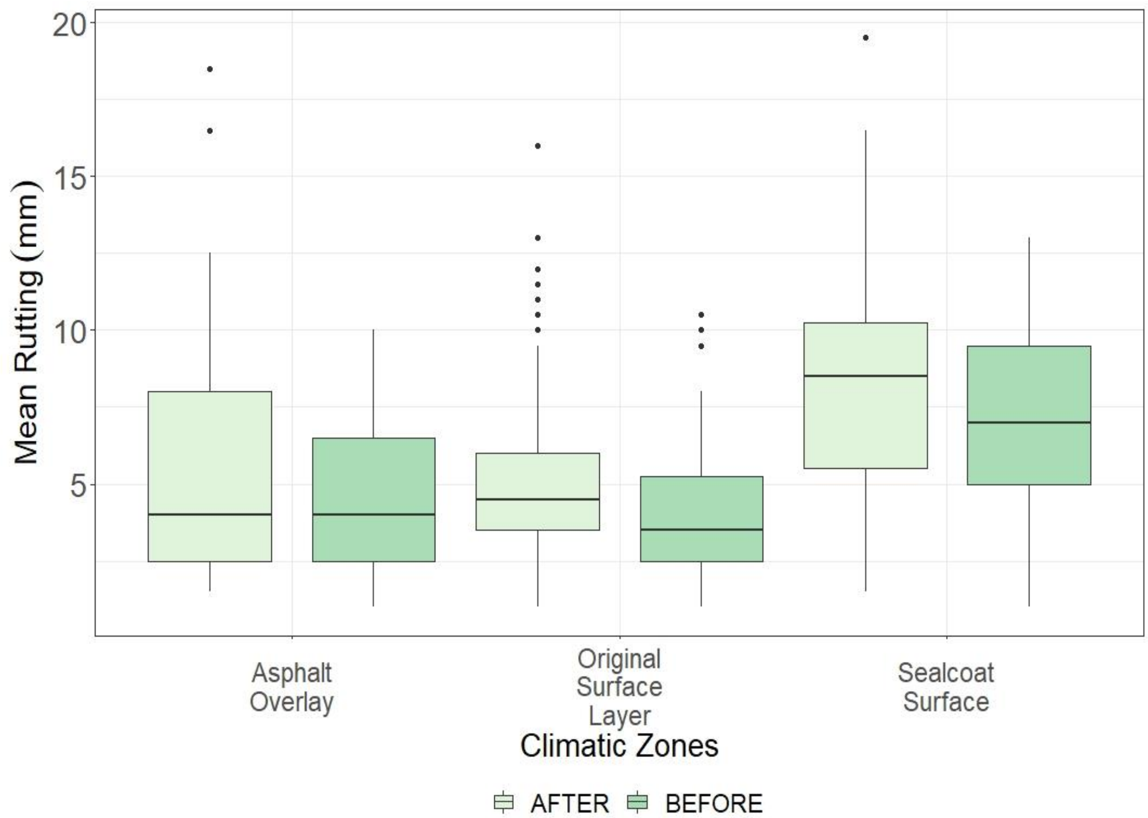

Figure 25. Mean Rutting Change in Existing Pavement Surfaces (Before & After)

Out of the three existing surface types, rutting value measured is higher in seal coat surface even before and after the treatment compared to asphalt overlay and original surface layer as shown in Figure 25. In asphalt overlay, the rutting value has remained unchanged even before and after the treatment. But in the original surface layer, a slight increase is observed, whereas high an increase in rutting is observed mostly in seal coat surfaces.

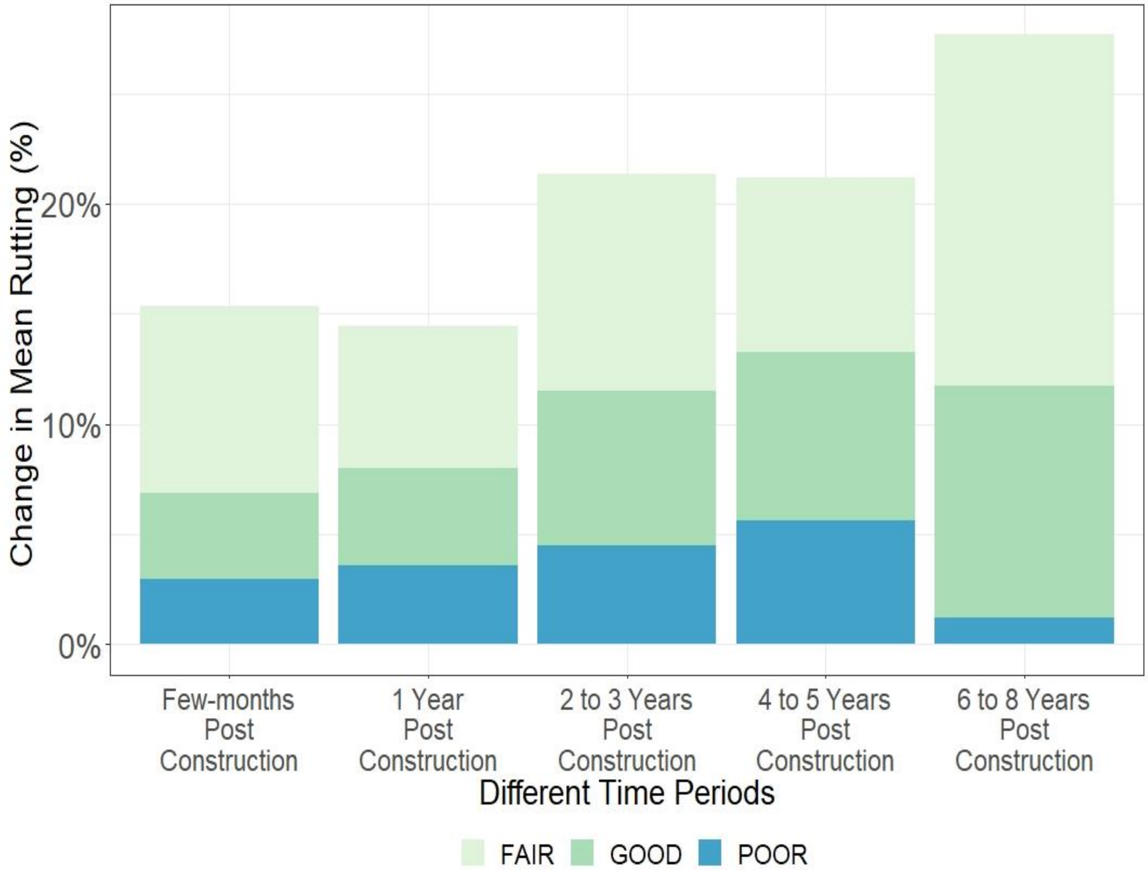

Figure 26. Mean Rutting Change with Pavement Condition Index

The pavement condition threshold is used for rutting which categorized the mean rutting values into good (<5.08mm), fair (5.08mm to 10.16 mm) and poor (>10.16 mm). Rutting has slightly increased over time after the application of chip seals as shown in Figure 26. The rutting has decreased in the 6^{th} to 8^{th} year period due to the effect of other maintenance treatment applied on those pavement sections.

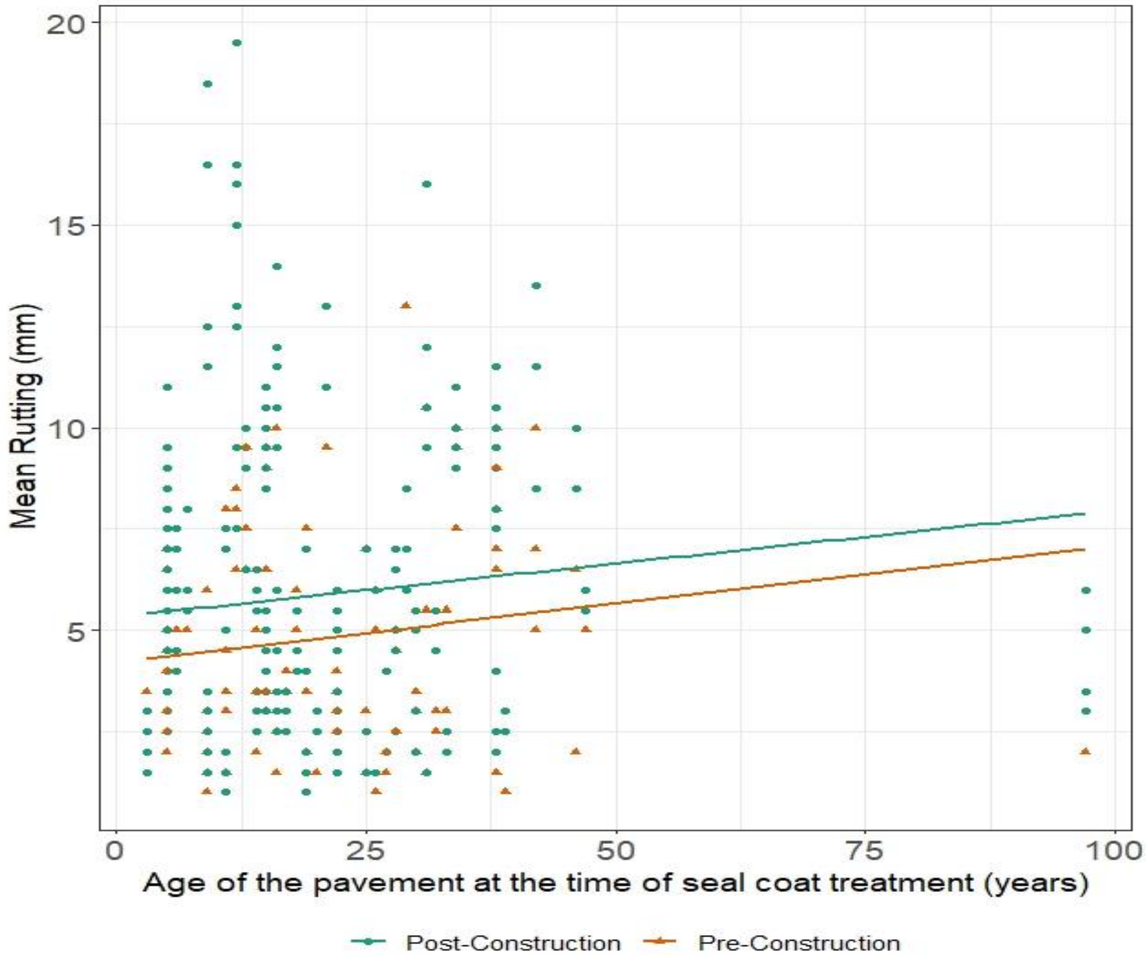

Figure 27. Mean Rutting Change with Pavement Age

The statistical test result showed that pavement age is not a significant variable that affects rutting in seal coated pavements. Before and after the treatment, the trend line in Figure 27 is parallel even though the rutting value has increased slightly after the treatment but rutting is increasing at the same rate as before the construction of chip seals.

3.4. Austroads

Australia has been monitoring long-term pavement performance for more than 20 years. Austroads (representing federal, state, and territory road agencies, local government, and the New Zealand road agency) funded the research to improve the understanding of pavement performance, promote and provide cost-effective and appropriate construction practices. The LTPP monitoring program measured performance by rutting, roughness, cracking, and deflection is recorded in Austroads database. The Austroads long-term pavement performance (LTPP) study involves monitoring pavement performance under different loading and environmental conditions at specific sites. Austroads took the opportunity to participate in the Strategic Highway Research Program in 1994/95 by establishing and funding its own LTPP monitoring program through a project later known as AT1064 Long-term Performance Monitoring to develop Consistent Performance Models as part of the National Strategic Research Program (NSRP). Later in 1998/99, they created long-term pavement performance maintenance (LTPPM) sites as a part of AT1064, also funded by Austroads. LTPPM sites are designed in such a way that the only the parameter of interest (i.e., maintenance) is varied at each site and other pavement characteristics remained constant. LTPPM study was set up to investigate the influence of various maintenance treatments on pavement performance at specific sites. The LTPPM sites are different from LTPP because these sites are 1km in length and were set up on highway across Australia to assess the effect of maintenance treatment on pavement performance. Each site consists of five adjacent 200 m long sections, all with the same pavement composition, but with a different surface treatment. These sites are known as the Long-Term Pavement Performance Maintenance (LTPPM) sites. While the LTPP sections are generally 150 m long, except for the lengths of ARRB1 with 200m.

Figure 28. Pavement Sections in Australia

Altogether, 11 test sections treated with chip seal (Spray Seals) are selected for this study. Out of 11 sites, 6 sites are LTPP sections and 5 sites are LTPPM sections. As we can see in Figure 28, the color denotes different sites where the red ones are LTPP sites and yellow ones are LTPPM. The information related to pavement section are provided in Table 10.

Table 10. LTPP and LTPPM Sections Details (Australia)

Sites	States	Types of seal coat Treatment	AADT	% of Heavy vehicles	Annual Average Temperature(°C)	Average Rainfall (mm)
ACT01-P1	ACT	Normal Reseal	4500	3	20.55	720.8
ACT01-C1	ACT	Normal Reseal	4500	3	20.55	720.8
ARRB1	QLD	Normal Reseal	1128	8.1	23.65	1323.8
ARRB2	NSW	Normal Reseal	4060	8.4	20	611.2
NS24	NSW	Normal Reseal	9040	15.1	24.54	1135.8
NS25	NSW	Normal Reseal	9040	15.1	24.54	1135.8
LTPPM2	VIC	S2-Normal S3-Geotextile S4-Scrap Rubber	2909	42.1	22.58	447.2
LTPPM3	VIC	S2-Normal S3-Scrap Rubber S4-Geotextile	-	-	-	-
LTPPM4	VIC	S2-Modified Binder S3-Modified Binder S4-Normal	1580	14	21	700.8
LTPPM5	QLD	S3-Normal S4-Reseal with surface correction S5-PMB	1894	14	28.7	2057.4
LTPPM6	QLD	S3-Normal S4-Reseal with surface correction S5-PMB	1605	14.5	29.51	1354.2

Table 12 contains general information about LTPP and LTPPM sites in Australia. The sites are located in four states, which are Victoria, Queensland, New South Wales, and Australian Capital Territory. Mostly, the states in the northern part (QLD, NSW) is warmer than states in the south (VIC, ACT). High rainfall occurs in Queensland than other states. LTPPM sections have six different types of seal coat treatments. They are normal reseal, geotextile reseal, scrap rubber reseal, modified binder reseal, polymer modified binder reseal, and reseal with surface correction. However, LTPP sites only use normal reseal. The performance of different seal coat treatments are statistically analyzed. The differences in performance of various types of chip seal on different distresses can be observed from Figures 29 through 31. The findings from this data are listed below:

- Out of six types of seal coat treatment, polymer modified binder reseal, scrap rubber reseal and geotextile provide lower rough surface than other treatments. The Kruskal-Wallis H test on different treatment groups showed that normal reseal and reseal with surface correction, scrap rubber reseal showed the same kind of performance and are not statistically significant. Highest MRI can be observed in modified binder reseal.
- There is not much difference observed in case of rutting depth of treatments. However, modified binder reseal has shown lower rutting among different types of seal coats treatments.
- Low percentage of alligator cracks are present in all the pavement sections. The highest alligator crack extent is 2.3%. And most of the cracks range from 0.02 to 0.86%.
- Similarly, medium longitudinal cracks and transverse cracks are observed for some of the sections. Not all sections have these types of cracks.
- Ravelling is observed more in polymer modified binder reseal while scrap rubber reseal and reseal with surface correction showed better performance. Flushing extent

above 25 % is found in geotextile while PMB reseal also has flushing greater than 20%. All other treatments have small amount of flushing.

- Transverse cracks are not observed in all types of seal coat treatments. However, very less percentage of transverse crack is observed in normal reseal and scrap rubber reseal.

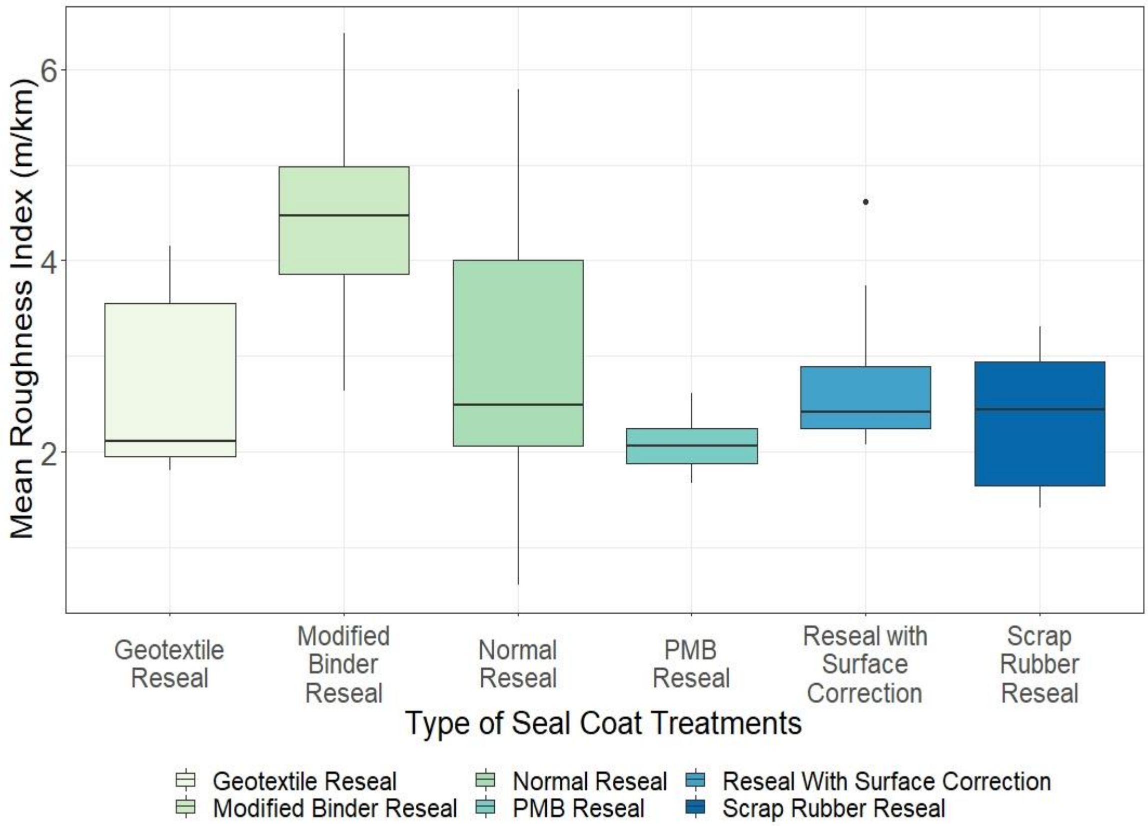

Figure 29. Mean Roughness Index - Types of Seal Coat Treatment

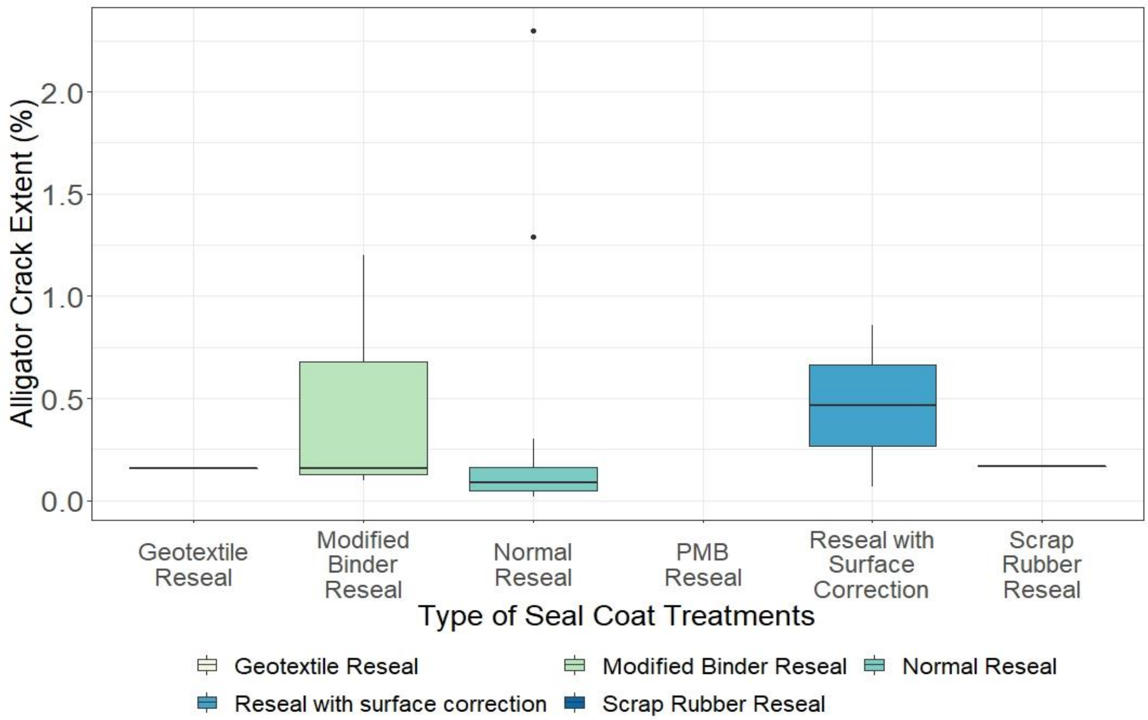

Figure 30. Alligator Crack Extent - Types of Seal Coat Treatment

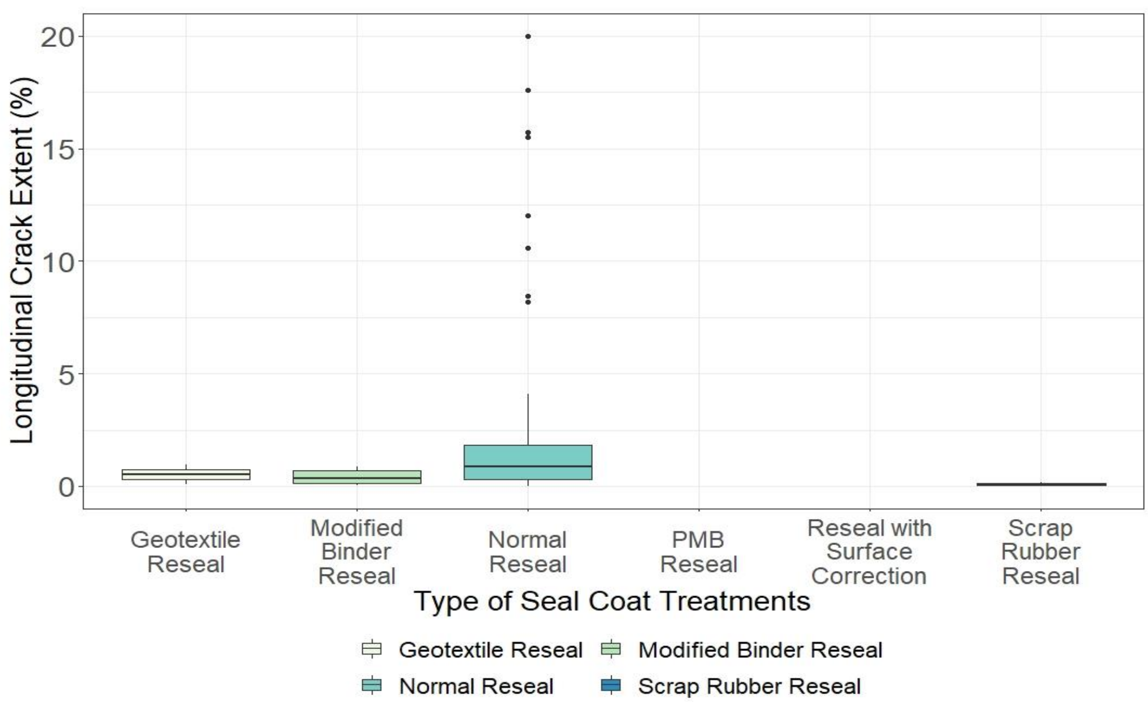

Figure 31. Longitudinal Crack Extent - Types of Seal Coat Treatment

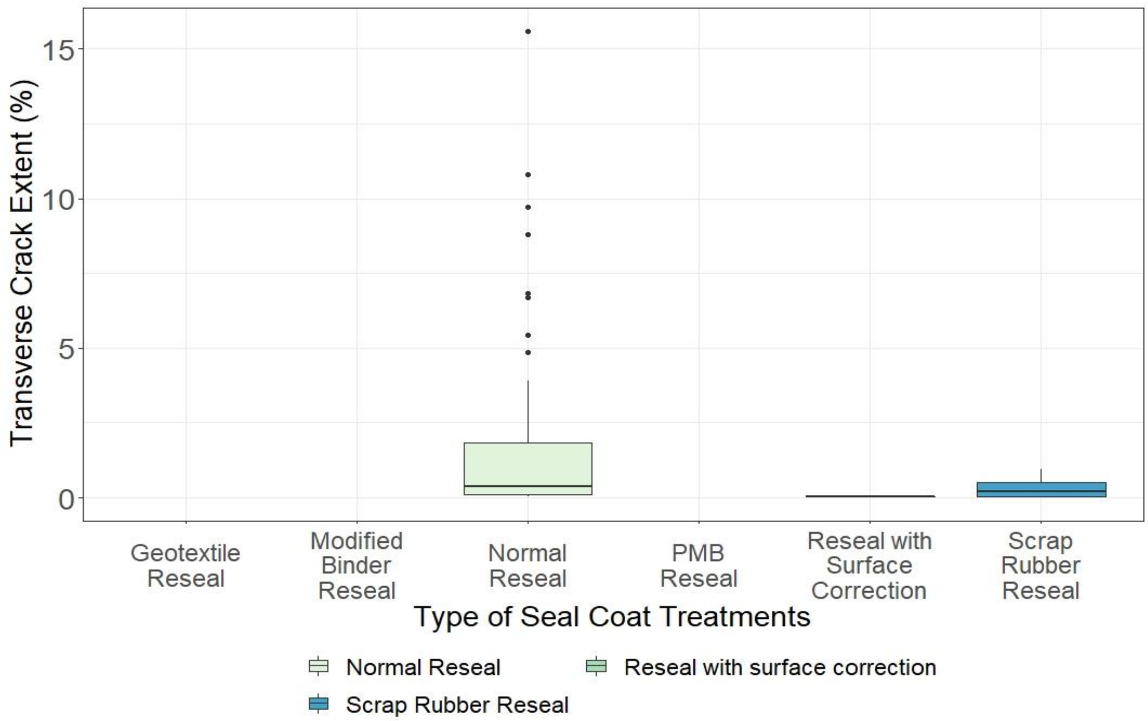

Figure 32. Transverse Crack Extent - Types of Seal Coat Treatment

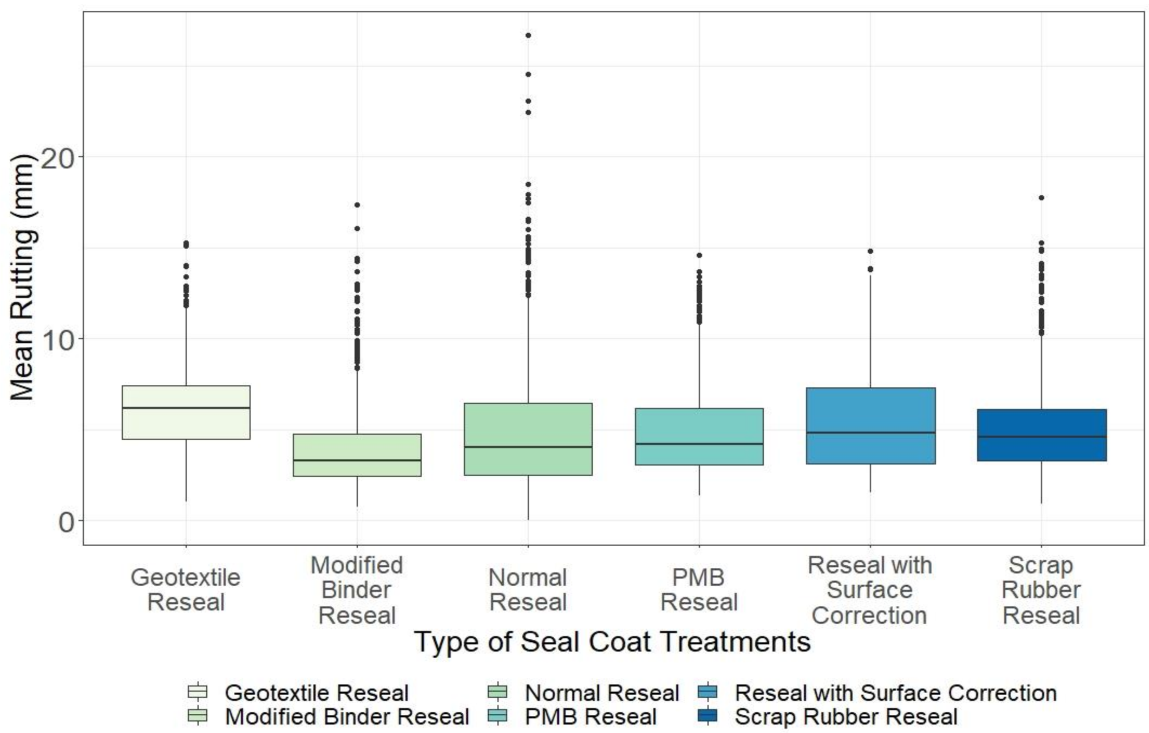

Figure 33. Mean Rutting - Types of Seal Coat Treatment

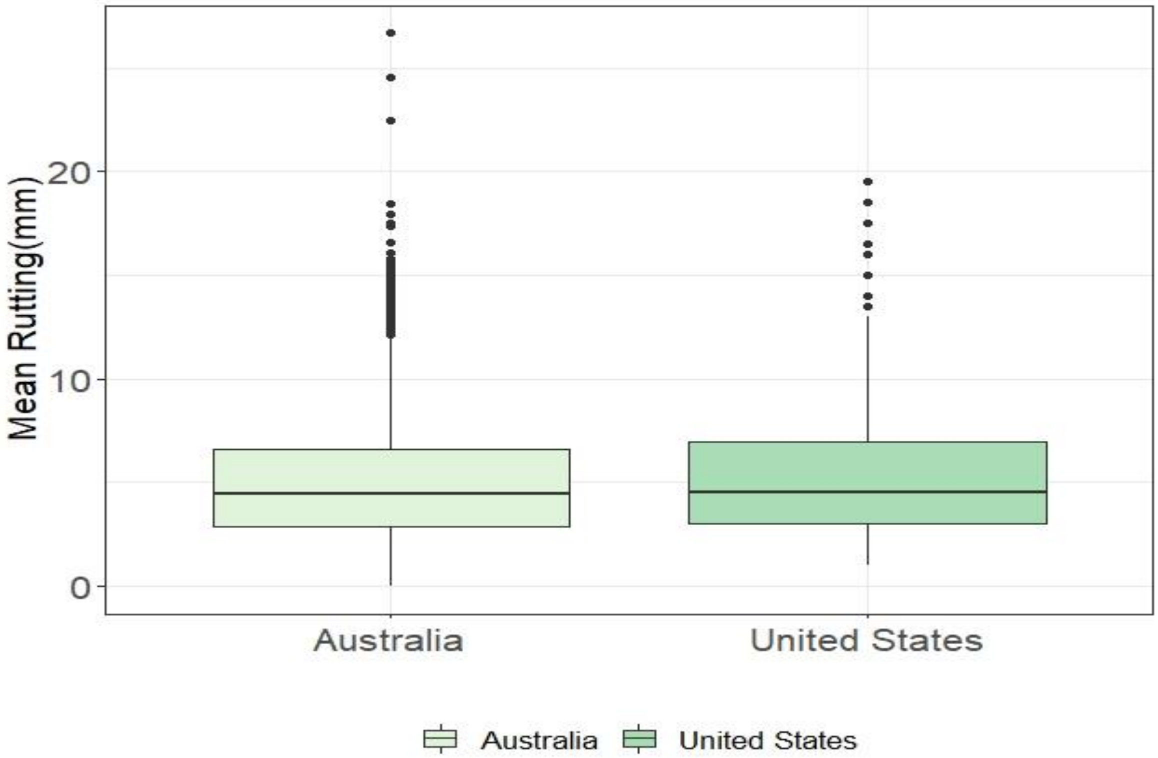

Figure 34. Mean Rutting: United States & Australia

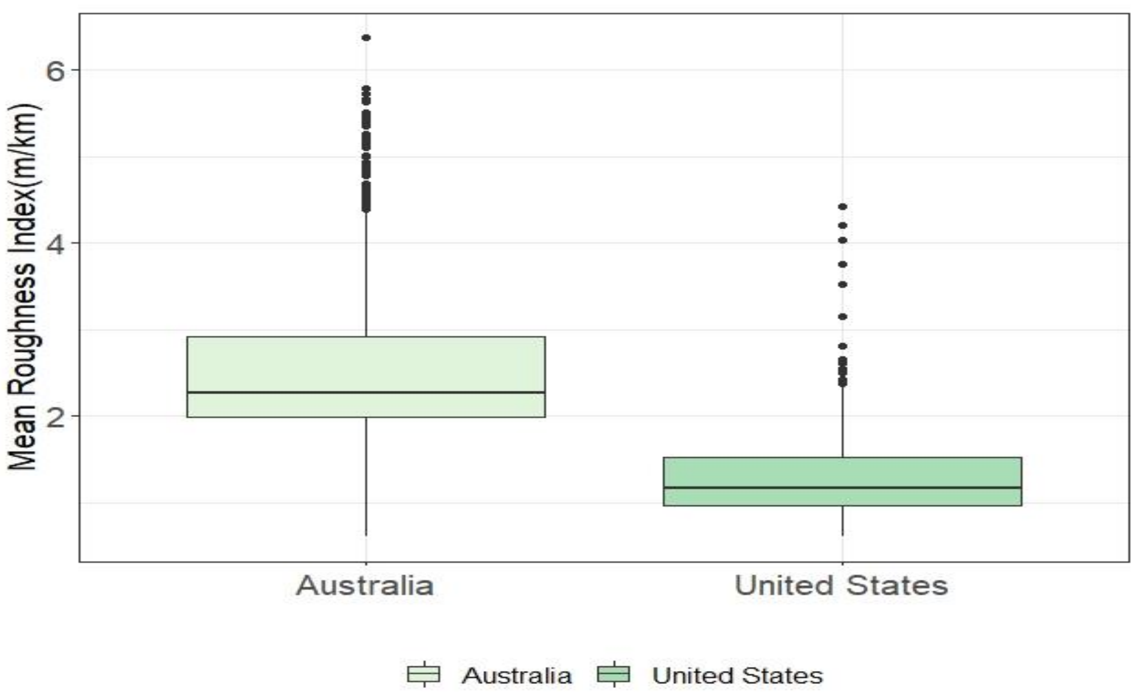

Figure 35. Mean Roughness Index: United States & Australia

4. RESULTS AND DISCUSSION

4.1. Linear Model for Roughness and Rutting

The linear models are used to understand the effect of predictor variable (AADTT, precipitation, temperature, pavement age, thickness, pavement existing condition) on rutting, roughness after one year of the application of chip seals. Cracking data are not included in the model due to many zero measurements in the data than the model allows for which will cause zero inflation to the distribution of the model. However, transformation also does not work well in case of lots of zero variable and will be really hard to explain what going on with the data. Hence, they are not included in the model but other tests are used for those data to find out the effects of treatment on cracking. The normality Q-Q, residual versus fitted, scale-location, and residual vs leverage plots for roughness and rutting are shown in Figure 35 and Figure 36. The normality plot for rutting and roughness shows residuals are normally distributed. From the residual versus fitted plot, we can clearly see equally spread residuals around a horizontal line without patterns which is a good indication that there is no presence of non-linear relationship.

For roughness, the most influencing variables are MRI before the treatment, pavement age at the time of treatment (years), annual temperature, existing pavement surface types, and annual precipitation. However, MRI before the treatment and pavement age explains the models better than other variables. In Table 11, the p-value of less than 2.2e-16 signifies that there is a strong relation between MRI value after the treatment with the MRI before and pavement age. The r-squared value of 0.8621 denotes that 86% of the variance found in the MRI after the treatment can be explained by MRI before and pavement age. The statistics provides a measure that the actual data are well fitted by the model.

Similarly, precipitation, AADT, annual temperature, and existing pavement condition are significant variables. But in case of rutting, simple linear regression is preferred using only one variable which is rutting value before the treatment. The p-value of 1.28e-15 in Table 12 shows that the model is significant and 77% of the variability is alone explained by pavement rutting before the treatment.

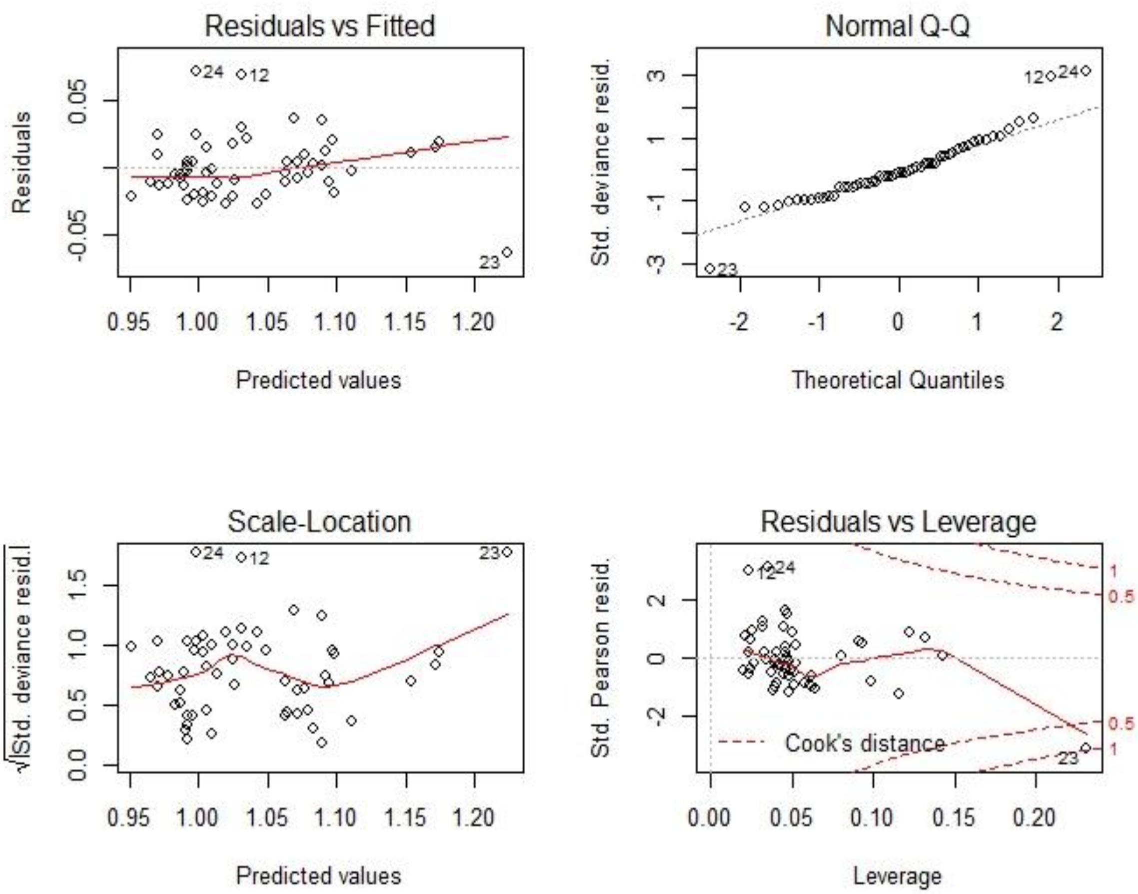

Figure 36. Roughness Model

Model Equation: $(\text{MRI after treatment})^{0.1818182} = 0.8658190 + 0.1351542*(\text{MRI before treatment}) + 0.0006794*(\text{Pavement Age})$

Table 11. Roughness Model

Variables	Coefficient Estimate	Standard Error	T-value	P-Value
Intercept	0.8658190	0.0098464	87.933	<2e-16***
MRI after treatment	0.1351542	0.0084335	16.026	<2e-16***
Pavement Age	0.0006794	0.0002316	2.933	0.00498**

Residual standard error: 0.02322 on 52 degrees of freedom

Multiple R-squared: 0.8672, Adjusted R-squared: 0.8621

F-statistic: 169.8 on 2 and 52 DF, P-Value: < 2.2e-16

<u>Rutting Model</u>

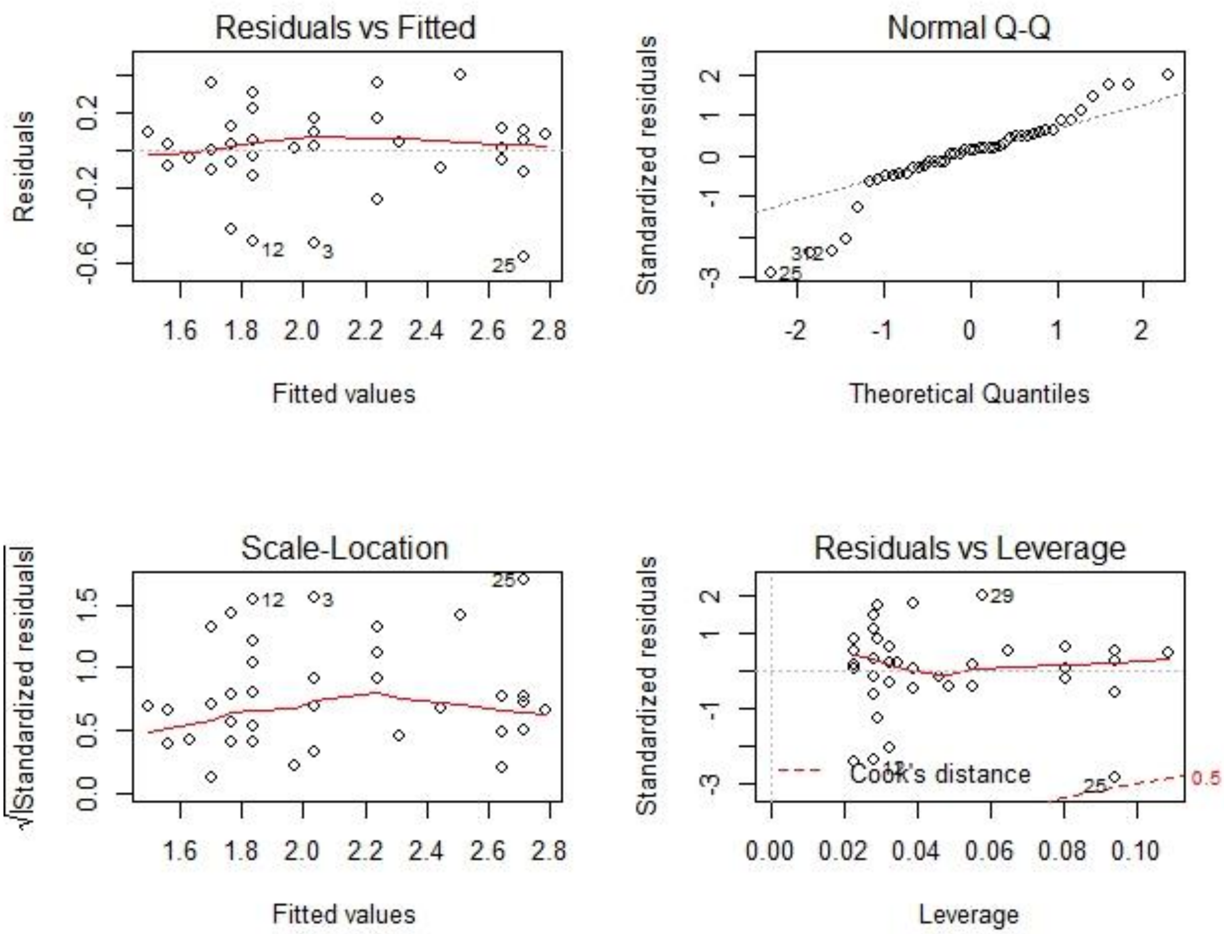

Figure 37. Rutting Model

Model Equation: $(\text{Rutting after treatment})^{0.4242424} = 1.35957 + 0.13561 * (\text{Rutting before treatment})$

Table 12. Rutting Model

Variables	Coefficient Estimate	Standard Error	T-value	P-Value
Intercept	1.35957	0.06283	21.64	<2e-16***
Rutting before treatment	0.13561	0.01106	12.26	1.27e-15***

Residual standard error: 0.2102 on 43 degrees of freedom

Multiple R-squared: 0.7775, Adjusted R-squared: 0.7723

F-statistic: 150.2 on 1 and 43 DF, P-Value: 1.268e-15

4.2. Field Performance Results

Data Analysis conducted using the field data from LTPP and Austroads highlights the changes in performance and effectiveness of seal coat. The performance of chip seals varies accordingly for every distress. The performance also varies in different regions and climate zone, pavement surfaces, and along with pavement ages. The performance observed in rutting and roughness showed that though the treatment might not reduce these both distresses, it also does not severely affect them to cause any major damage to the pavements. There was no significant change observed in the mean roughness index over a period of time. But the noticeable difference in MRI values seen in two different regions. However, no such distinction in MRI over eight-year time period is found in two regions. The only difference found was the contrast in roughness values noted in north and south. Mostly, MRI values are much higher compared to the north. And the reason could be due to the larger size of aggregates used for seal coat treatment in the southern part. The maximum aggregate size of 19.05,15.875 and12.7 mm is mostly used in the south, whereas 12.7, 9.525 mm is the most common aggregate size utilized in the northern regions. Further, chip seal effectiveness is also evaluated in various climate zones to get a better understanding of the variation of roughness performance. The result from the Kruskal-Wallis test showed roughness difference in climatic zones is statistically significant. Temperature, precipitation, and freeze-thaw cycles greatly influence MRI. The higher roughness values were observed in the wet-freeze zone. The roughness progression is accelerated by freeze-thaw effects and trapped water. In the wet-freeze zone, the presence of water affects roughness and freezing water in the pavement causes additional stress and deterioration in the pavement structure. The MRI after the treatment in the wet freeze region has remained same as before not showing any higher progression. The condition of the pavement before the treatment is a major factor for the success of chip seals. Pavement condition thresholds are used to evaluate performance measures. The roughness measurement is categorized in terms of good (<1.5), fair (1.5-2.68), and poor (>2.68) m/km conditions. Pavement sections that are in good condition have performed well throughout the eight years. However, pavement section which is in fair condition but with threshold value not above 2m/km worked better for a long time period after using chip seals. However, pavements which are in fair condition but have a threshold greater than 2m/km showed fair condition after 1 yr of the treatment and then start degrading with a higher rate from 2nd year of the treatment. Hence the pavement section had fallen into the poor category in 2nd year and later this increase in roughness will degrade the chip seals surface and also result in dislodging of aggregates, and ravelling. Further, the pavement section which already have seal coat as a surface layer have shown higher roughness than other layer types. It is known that roughness would steadily increase in the pavement but after the application of chip seals, there would be a very slight increase in roughness due to the size of aggregate placed directly on top of binder. And it is known that asphalt overlay and HMAC surface layer have a smooth surface compared to seal coats. That's why, higher roughness before the treatment is observed for pavement which has existing seal coat as a surface layer and chip seal placed on that existing seal coat surface would certainly have more roughness when compared to other pavement surfaces. The rate of increase in roughness is slightly higher in older pavement treated by seal coats than in younger pavement as shown in Figure 9. The age of pavement at the time of treatment of seal coat is one of the significant variables.

No significant change in rutting over time is observed in the pavement sections. And this is already known that seal coat treatment is not effective in treating structural damage of pavements. However, the treatment can preserve the structural capacity of the pavement. Similar to roughness results, rutting seems to be quite higher in the southern region than north. Pavement sections in the south are subjected to warm weather, whereas northern parts are much more colder. In the south regions, pavements are exposed to hot temperature, and the pavement mostly begin to expand in such weather. And when this happens, once heavyweight or constant repetition of traffic loading on the surface layer, the asphalt will sag and form a depression, resulting in rutting. This phenomenon may have increased rutting in the southern regions.

All of the pavement sections used in this study have shown improvement in cracking after few months and one year of the treatment, slowly forming cracks from 2nd year due to traffic and environment exposures. Moreover, chip seals are not expected to improve structural capacity of the pavement. However, it appears that chip seals have worked well in reducing alligator cracking and longitudinal wheel path cracking. The results showed that the cracking area is completely sealed in the few months and 1st year after the construction. A very little increase in cracks is seen in the 2nd year, and then cracking rate is higher in the 4th to 5th year. On the other hand, initial Longitudinal NWP cracking and transverse cracking are much higher that is why they are visible early in the first year of treatment. But the decrease in Crack length after the treatment has been seen in almost all pavement sections.

Similarly, another observation is the difference in the performance of cracking in two different regions. Cracking measurements are quite higher in the cold climate in the northern part as compared to south. Usually, in the northern part, the temperature can fluctuate above and below freezing; while there may be not be any precipitation on the ground, there could be some still underneath. If snow seeps into a cracked area of asphalt, and the temperature warms, then it results in water and once the temperature drops again, the water freezes and expands, pushing the cracks outward. This freeze-thaw process can widen already made cracks. This could have resulted in more cracks in the northern region than the southern region. However, the percentage of cracks has reduced at the beginning due to seal coat but then the cracks are increasing at a higher rate in the second year of the treatment. Furthermore, it is found that more than 10% of cracks present before the treatment in most of the northern sections have resulted in poor performance. Moreover, another reason for less crack present in the south sections is that they applied crack seal before using chip seals to completely seal severe crack so that chip seal can have a good service life. Hence, the existing pavement condition is one of the critical factors that would play a significant role in chip seals' performance. Different statistical tests and regression analysis were conducted to understand the factors affecting chip seal performance. Regression models for roughness and rutting of one year after the treatment were developed. It was found that pavement age at the time of treatment highly influences roughness. Temperature and precipitation were found to significantly affect the chip seal performance.

Seal coat treatment has been found to be very useful in sealing cracks in both countries. In Australia, a lower percentage of alligator cracks are noted. Moderate longitudinal cracks and transverse cracks are observed after years of treatment. Moreover, very few cracks are observed in Australia than in US, Since they are using multiple layer seal coats with lots of modification using different types of binders, material to prevent damage from various factors such as environment as well as heavy traffic Also, the thickness of the seal coat layer is twice the thickness used in US. The seal coat thickness ranges from 0.2 inches to 0.6 inches in US where thickness of 0.9 to 1.5 inches are used in Australia. Statistical difference in performance is seen in roughness in both countries. Australia have high roughness in comparison to the US as shown in Figure 34. Multiple-layer application of binder and aggregates are more common in Australia whereas all of the US pavement sections used in this study are single layer seal coats. In Australia, the aggregate size of 10mm and 14mm for single layer seals are usually used when there is sufficient traffic to provide required embedment depth. And in case of lower traffic, 7 mm aggregate is sufficient. Moreover, most of the sections used in this study are multiple-layer reseals. And they primarily use 16mm and 20mm aggregates in combination with smaller size aggregates. Common combinations of aggregate in double/double and single/double seals are:

- 10 mm with a 5 or 7 mm aggregate
- 14 mm with a 5 or 7 mm aggregate
- 16 or 20 mm with a 7 or 10 mm aggregate

Among several treatments used in Australia, modified binder reseal showed very high roughness while it has low rutting. Modified binders are generally used to treat cracked pavements by alleviating the effect of mechanical strains that occur in the pavement. However, the binder if used with smaller aggregates will not be able to absorb the strain. Therefore, the use of larger aggregates size greater than 10 mm are preferred which could be the factor that have triggered roughness in pavements. However, polymer modified binder showed lower roughness, but this section has a high percentage of flushing compared to other treatment types. Geotextile Reinforced Reseal also showed higher flushing. Flushing usually occurs when asphalt binder fills the voids in the aggregate and comes up towards the surface but the binder will not be in liquid state rather it is in solid or semi-solid. It is known that geotextile and polymer modified binder is more susceptible to temperature and heavy rainfall. But no significance difference in rutting depth is observed in two countries which can be observed in Figure 33. Australia have given more emphasis on chip seals because they believe that chip seal has great potential for enhancement and can provide long service life if designed and constructed properly. They use various chip seals on pavement sections depending upon weather, pavement conditions, amount of distress and traffic levels. Hence the same level of technical engineering support is needed for chip seals in US to provide updated research on design techniques and performance evaluation of chip seals treatment.

5. CONCLUSIONS

This study aimed to evaluate the effectiveness of chip seals treatment in terms of distresses that were measured in the pavement field and saved as pavement performance data in the LTPP database and to compare the performance and variations of pavement surface conditions due to seal coat treatments in two different countries.

LTPP field data evaluation of pavement sections in the US with chip seals in different states showed that even with the variation in design, material and with best chip seal practices, the common and most important thing that the seal coat performance depends on is the condition of existing pavements before the treatments. Chip seals are not intended to improve rutting and roughness in pavements. However, it is also observed that roughness and rutting in seal coated sections have not increased at a rapid rate as long as the existing pavements are in good conditions. Moreover, the performance dependence on existing pavement condition also applies in case of cracking, where severely cracked pavement starts to show a significant amount of cracking even within the first year of the treatment. And thereafter, cracking starts increasing rapidly. In contrast, higher benefits of seal coat treatment are observed on good pavements conditions with minimum acceptable levels of pavement distress when considered over an extended period of time. The effectiveness of seal coat treatment depends on the initial pavement condition and is a crucial factor to consider while applying a chip seal treatment.

Seal coat treatments are found very effective in reducing minor cracks. The result showed that most chip seals are effective in preserving the surface from the development of cracks for two years. After that period, minor cracks start to form, but the deterioration rate is still lower. Besides, the difference in the performance of seal coats are observed in two regions i.e. north and south in the US. Southern regions have very high roughness and rutting, while more cracks are observed in northern regions. The variation in climate of two regions has played a major role in the performance difference of seal coats. Hence the study of field data from nine states in the US has provided valuable information regarding the performance differences of chip seals seen in different regions along with the change in performance over time. These important insights of a chip seal performance in pavement sections from different states will help in the construction and design of new seal coats and also incentivize particular measures to be specially taken in colder regions to mitigate cracks and extend the life of the chip seals treatment.

The comparison of field performance of chip seals in the US and Australia has provided useful information regarding the field performance of chip seals in the two countries. Although the design methods and construction practices are quite different, Chip seals have performed well in both the US and Australia. Multiple layer chip seals are very common in Australia where various types of multiple layer chip seals are applied to the pavements to address distresses under different environments and traffic conditions. A very small percentage of cracking is observed in Australia as compared to the US and they have used chip seals to their highways and heavily trafficked pavements. These several types of chip seals can also be applied in the US depending upon the pavement conditions and the needs of the pavements to address various distresses. In order to incorporate this goal, more extensive research should be employed to assess various types of chip seal treatments to find out how effective those treatments would work in the United States. The Australian engineering advancement in chip seals treatment could guide us to develop techniques to improve the performance and quality of seal coat treatments here in the US.

The evaluation of the effectiveness of chip seals treatments over a period of time, in different climatic regions and comparison of field performance with international community that predominantly use chip seals in asphalt pavements is vital for both pavement construction and maintenance management and could provide a different outlook to develop a new approach to successful chip seal practice in the United States. The findings in this study have proven that chip seals are economical and yet effective maintenance strategies in preserving pavement surface from further cracking and deterioration. Chip seal design requires further understanding of properties of the material such as aggregate gradation, size, shape, and characteristics of different binder types with or without other additives to estimate proper binder application rates and aggregate rates considering cracking, rutting, bleeding, flushing, and raveling in pavements. Hence, a further in-depth study is needed along with an appropriate statistical approach that should be used to understand the various factors affecting the performance of chip seals.

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