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Service Life Enhancement of Substrates Overlaid with Thin Overlays (UTBWC, Chip Seals, and Micro-Surfacing)

NRRA PREVENTIVE MAINTENANCE TEAM

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16. Abstract (Limit: 250 words)

Non-structural overlays such as ultra-thin bonded wearing course (UTBWC), chip seals, and micro-surfacing are commonly applied as a preventive maintenance method to extend the service life of a pavement. They are generally placed over flexible substrates, which include flexible pavements that have received bituminous interventions on bituminous upper layer (BOB), flexible pavements that have received bituminous interventions on concrete layer (BOC), and flexible pavements that have not received any intervention since constructed on aggregate base (BAB). These treatments have been widely applied, thus driving the need to conduct an analysis to determine the service life enhancements of these overlays using Weibull analysis. There are various factors that affect the expected service life of these preventive maintenance techniques such as the condition of the substrates and the maintenance window. The RSL – service life enhancement since intervention – for all treatments from two agencies (MnDOT and NDDOT) appear to be relatively close to each other, except for the BOC substrates overlaid with micro-surfacing. All treatments have a pattern of wear-out failures, which are an indication that the treatments are effective in providing life extensions because the cause of failures is not random. Some of the interventions are second or third and these collectively synergistically improve service life of the substrate, for which further investigations are recommended. Additional data from other state members and an update on these existing data (MnDOT and NDDOT) in five years would enhance the performance curves and improve the accuracy of estimated remaining service life.

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FINAL REPORT

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CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

Non-structural overlays such as ultra-thin bonded wearing course (UTBWC), chip seals, and micro-surfacing are commonly applied as a preventive maintenance method to extend the service life of a pavement. They are generally placed over flexible substrates, which include flexible pavements that have received bituminous interventions on bituminous upper layer (BOB), flexible pavements that have received bituminous interventions on concrete layer (BOC), and flexible pavements that have not received any intervention since constructed on aggregate base (BAB).

UTBWC, also known as "NovaChip," is an application of gap-graded hot mix asphalt (HMA) over a layer of polymer-modified emulsion. UTBWC has been proven to be an effective surface layer; its gap graded membrane provides drainage and prevents moisture from flowing through, yet it is still flexible. The bottom emulsion membrane is durable and has good cracking resistance, which will help to prevent cracks from reflecting through. This treatment can be applied on both HMA and Portland cement concrete (PCC) roads.

Chip seals involve an application of asphalt emulsion directly to the pavement surface, immediately followed by an application of a layer of aggregate chips. Although chip seals do not provide any structural capacity to the existing pavement, they help to seal the surface of the pavement from oxidation and infiltration of moisture and incompressible materials. This treatment can be applied to asphalt surfaced pavements.

Micro surfacing is a mix of crushed aggregate, mineral filler, additives, water, and polymer-modified emulsified asphalt. Since micro surfacing contains chemical additives, it can break without relying on the sun or heat. Micro surfacing is effective at sealing low-severity cracks and addresses issues such as friction loss, moisture infiltration, bleeding, and roughness. This treatment is often chosen to inhibit raveling and oxidation, as well as improving surface friction and filling minor irregularities and rutting in a roadway. This treatment can be applied to asphalt surfaced pavements.

According to the Pavement Preservation and Recycling Alliance (PPRA), the typical life of an untreated road is 20 years (**Figure 1.1**). The condition of the road is predicted to decrease by 40 percent in the first 75 percent of the pavement's life. Thus, these preventive treatments are commonly applied to roads early in their pavement life to help extend the service life.

These treatments have been widely applied, thus driving the need to conduct an analysis to determine the service life enhancements of these overlays. There are various factors that affect the expected service life of these preventive maintenance techniques such as the condition of the substrates and the maintenance window.

This project includes the data collection efforts and analysis performed on performance, remaining service life, reliability, and added effects and/or benefits of non-structural overlay interventions. The pavement conditions of these overlays have been evaluated using measurements such as Ride Quality Index (RQI) and International Roughness Index (IRI). The applicable analytic methodology that has been selected to determine the pavement performance is the Weibull analysis.

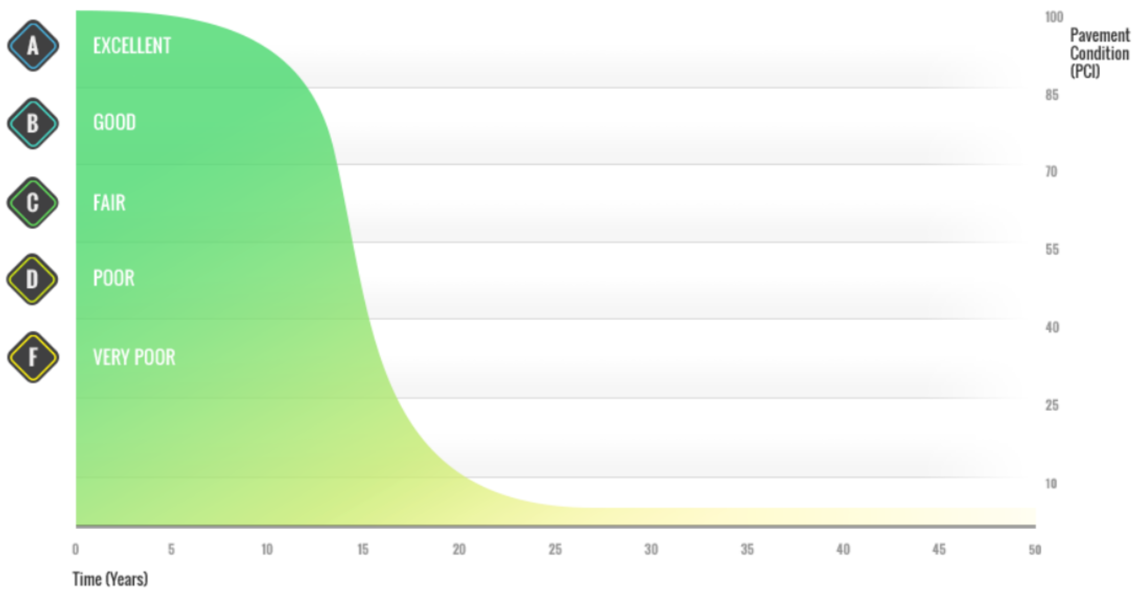

Figure 1.1 Pavement degradation curve of an untreated road obtained from the PPRA. Source: PPRA, 2020.

1.2 SYNTHESIS

The Minnesota Department of Transportation (MnDOT) has completed the analysis on the pavement performance of substrates overlaid with non-structural overlays (UTBWC, chip seals, and micro-surfacing). However, to generate a more developed system in predicting pavement performance, MnDOT has sent a survey and requested the National Road Research Alliance (NRRA) member states to gather their performance data, in which analysis results would be compared to MnDOT's results. North Dakota DOT (NDDOT) has provided 10-year performance data (2009 to 2018) from all eight districts (Bismarck, Devils Lake, Dickinson, Fargo, Grand Forks, Minot, Valley City, and Williston). Using the data collected, several indexes were analyzed in the Weibull analysis.

One of the pieces of performance data gathered was roughness, which was measured in terms of the International Roughness Index (IRI). IRI is obtained from the pavement profile measured using the front lasers of a data collection vehicle (MnDOT, 2015). The simulation of a standard traveling vehicle is used to obtain IRI, in which the value is derived from the gross vertical movement of the traveling vehicle aggregated over the length of the section investigated. The standard IRI is measured in inches per mile, i.e., inches of vertical movement experienced per mile traveled. The higher the IRI, the rougher the road.

Another performance index used was Ride Quality Index (RQI). RQI ranges from 0 to 5.0, where a higher RQI represents a smoother road. RQI is a conversion from IRI using regression analysis, with a customer's opinions considered (***Equation 1*** and ***Equation 2***). This correlation was generated based on the results from a rating panel. A rating panel consists of a group of panelists being driven over pavement sections and rate on how smooth the sections ride. ***Equation 1*** and ***Equation 2*** were in accordance with the conversions adopted by MnDOT's Pavement Management Unit (2015).

Bituminous Pavements

$$RQI = 5.697 - (0.264)\left(\sqrt{IRI}\right), IRI\ \left(\frac{inches}{mile}\right) \quad \boldsymbol{Equation\ 1}$$

Concrete Pavements

$$RQI = 6.634 - (0.353)\left(\sqrt{IRI}\right), IRI\ \left(\frac{inches}{mile}\right) \quad \boldsymbol{Equation\ 2}$$

Remaining Service Life (RSL) is an estimate of the service life of a pavement until its condition degrades to a specified threshold. MnDOT uses an RQI of 2.5 as the threshold, which is equal to a zero remaining service life. MnDOT's definition of RSL based on 2.5 RQI is used in this report.

The Weibull analysis has been utilized to evaluate the service life enhancement of substrates overlaid with non-structural overlays. To determine the configurations in the data that provide valuable information such as the effectiveness of the non-structural overlays evaluated and the optimal time to intervene for maximum resulting service life, performance graphs (RQI versus time) were plotted.

1.3 OBJECTIVE

1.3.1 NRRA Members Involved

Eight state agencies that are currently involved in the service life enhancement of substrates overlaid with thin overlays (UTBWC, chip seals, and micro-surfacing) include the California Department of Transportation (Caltrans), Illinois Department of Transportation (DOT), Iowa DOT, Michigan DOT, Minnesota DOT, Missouri DOT, North Dakota DOT, and Wisconsin DOT.

1.3.2 Objective

The purpose of this project is to determine the service life enhancements of the three non-structural overlays and deduce the service life enhancements that these non-structural overlays contribute to the identified substrates on which the overlays are placed based on the pavement management data from NRRA member states. This document is intended to serve as a living document, which in the near future if more data is collected from other state members, analysis can be performed to further improve and enhance the existing system in predicting performance of these non-structural overlays.

CHAPTER 2: RESEARCH METHODOLOGY

2.1 BACKGROUND OF WEIBULL DISTRIBUTION

Three reliability parameters that can be obtained from the Weibull analysis, analytically or graphically, are the Shape parameter or the failure pattern of the thin overlays, the Scale parameter or the service life of the thin overlays before reaching failure (in this analysis being this is being defined as the RQI reaching a value of 2.5), and the Location parameter or the threshold time to failure (in this analysis this is being defined as the amount of time from the application of thin overlays before distresses start to appear).

2.2 DATA SOURCING

2.2.1 MnDOT

The MnDOT pavement management data was available from the 1960s to 2017, and MnDOT researchers have extracted relevant datasets for each type of thin overlay with respect to the type of substrate. The number of data points obtained was summarized in **Table 2.1**.

Table 2.1 Number of datasets extracted from MnDOT pavement management data.

Type of Substrate / Type of Thin Overlay	BOB	BOC	BAB
UTBWC	84	52	0
Chip Seals	2263	600	459
Micro-surfacing	520	186	120

2.2.2 NDDOT

The NDDOT provided pavement management for all eight districts from 2009 to 2018, from which relevant datasets for each type of thin overlay with respective to the type of substrate were extracted. The number of data points obtained were summarized in **Table 2.2**. No UTBWC overlaid segments have been discovered from the pavement management data. IRI data obtained from the NDDOT pavement data were converted to RQI using *Equation 1* prior to the data assemblage process.

Table 2.2 Number of datasets extracted from NDDOT pavement management data.

Type of Substrate / Type of Thin Overlay	BOB	BOC	BAB
Chip Seals	204	0	24
Micro-surfacing	48	26	16

2.3 DATA ASSEMBLAGE

Performance curves were plotted for all pavement segments extracted, in which information such as RSL, time to rehab, spike of RQI at rehab, and condition at rehab or RQI were obtained from the curves. **Figure 2.1** displayed an example of a performance curve showing micro-surfacing performed at year 37 (**Figure 2.2**) in a pavement's life resulting in improvements in pavement conditions.

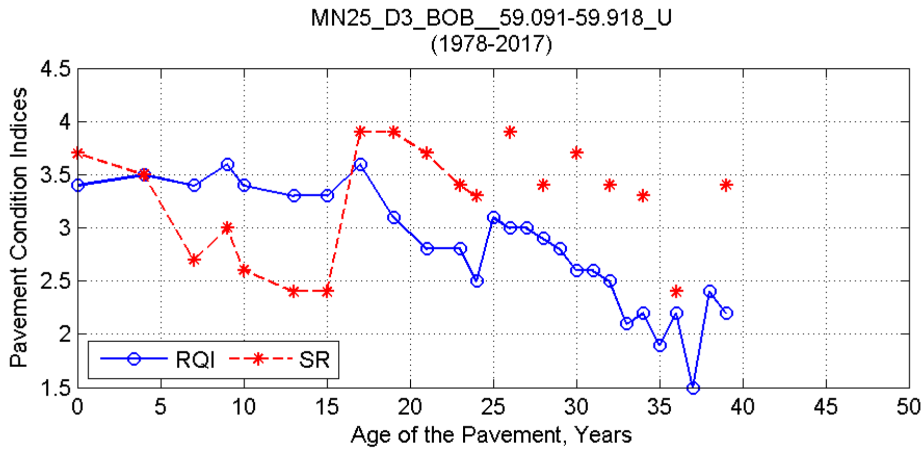

Figure 2.1 An example of a performance curve showing improvements in conditions at year 37, when micro-surfacing was applied.

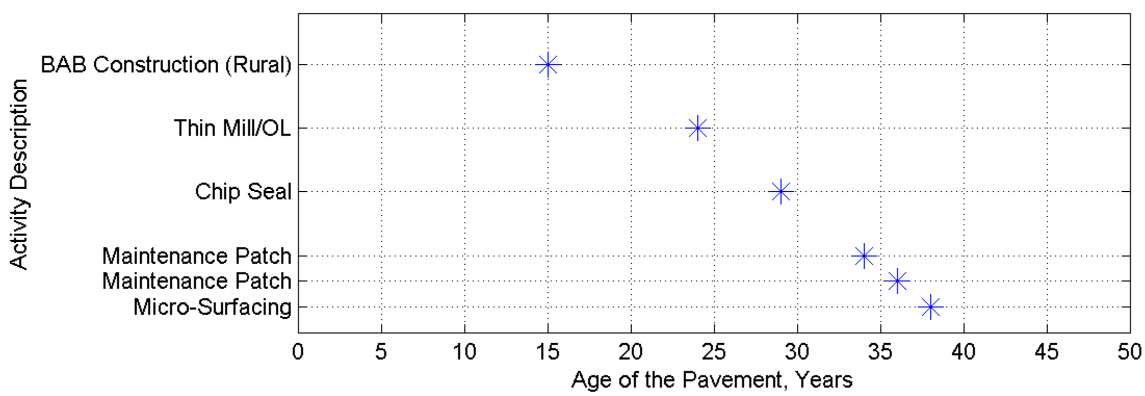

Figure 2.2 Activity description of the pavement, which performance was shown in Figure 2.1.

CHAPTER 3: RESEARCH ANALYSIS

3.1 WEIBULL RELIABILITY ANALYSIS

Figure 3.1 shows a typical performance curve that is enhanced to show the different parameters obtained for analysis.

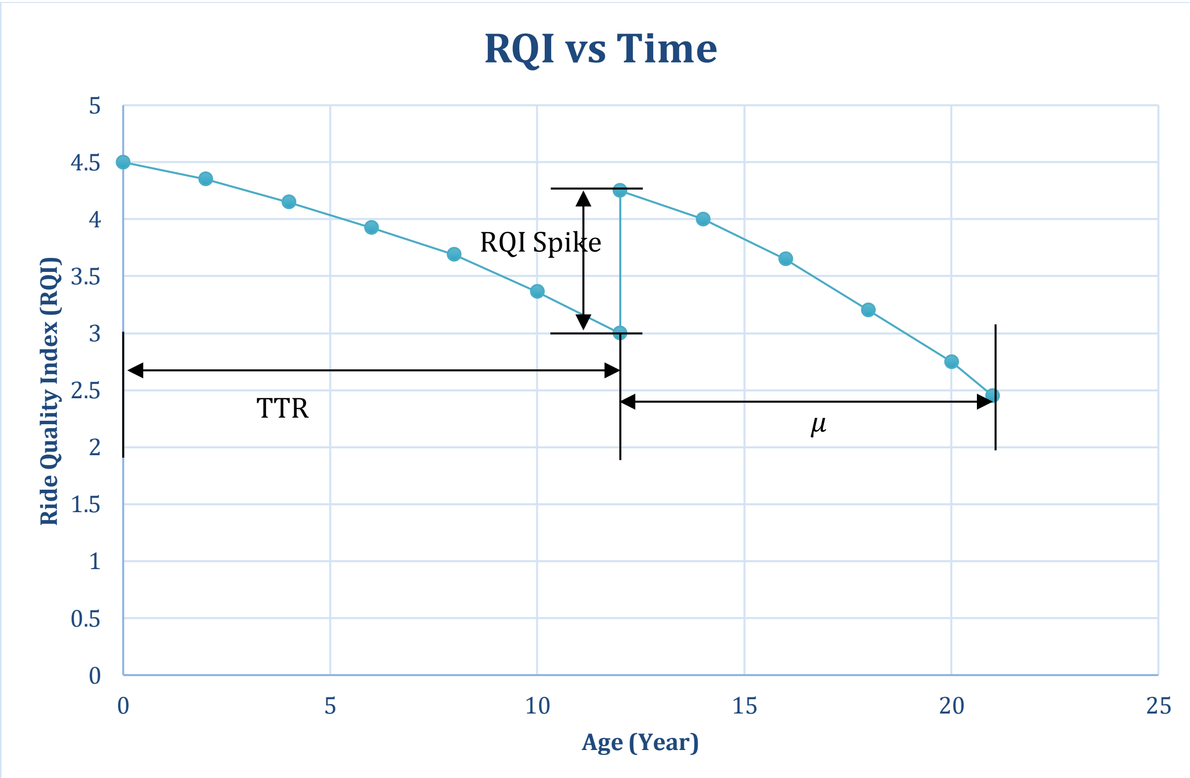

Figure 3.1 An example of enhanced performance curve, the data are not based on any projects.

The time to rehab (TTR) is the time from last rehab, could be mill and overlay or new construction, to intervention. The RQI spike is the increase in RQI due to the intervention. The RSL in this report is defined as the number of years since intervention for the RQI to drop to a 2.5.

For segments that have not reached an RQI of 2.5, the RSL for thin overlays were extended and obtained graphically from performance curves and the cumulative distribution function of these values was obtained. ***Equation 3*** shows the formula for Probability Density Function (PDF) and ***Equation 4*** shows the formula for Cumulative Density Function (CDF) (Izevbekhai, 2014; Izevbekhai, 2016; Izevbekhai, Farah, and Engstrom, 2020).

$$f(t) = \frac{\beta(t-t_o)^{\beta-1}}{\mu^{\beta}} e^{\left\{-\left[\frac{t-t_o}{\mu}\right]^{\beta}\right\}} \quad \textbf{Equation 3}$$

$$F(t) = 1 - e^{\left\{-\left[\frac{t-t_o}{\mu}\right]^{\beta}\right\}} \quad \textit{Equation 4}$$

Where β is the shape parameter; μ is the scale parameter; and t (or $t - t_o$) is the "time-to-failure". The variable t_o is the threshold time to failure, i.e. the time at which distresses begin to show.

The shape parameter, β, is Weibull slope, modulus, or shape. This value characterizes the failure distribution of the thin overlays. The failure modes associated with the shape parameter are summarized below (HBM Prenscia Inc., 2002). A higher β is typically a representation of a more successful treatment (Izevbekhai, 2018).

- β less than 1 signifies the failure rate decreases with time. It can also be classified as infantile or early-life failures.
- β close to or equal to 1 indicates the failure rate is relatively constant, which can be a sign of useful life or random failures.
- β greater than 1 denotes the failure rate increases with time, an indication of wear-out failures.

The scale parameter, μ, is the characteristic life. The threshold time to failure, t_o, is the actual time at which distresses begin to show up in the thin overlays. CDF was employed as it has been defined as the probability that a variable, in this analysis is RSL, is less than or equal to the argument.

Varying t_o values of 0, 1, 2, 5, and 6 were assumed and together with the RSL values were used in ***Equation 6*** to compute the natural log of the difference between the two values (Izevbekhai, 2014). By plotting ***Equation 5*** against ***Equation 6*** for each t_o, these different t_o values can be compared for accuracy. ***Equation 5*** and ***Equation 6*** linearize the CDF equation, in which the resulting plot generates a linear best fit line that we could extract the reliability parameters from (Izevbekhai, 2016). The most accurate t_o was indicated by the R^2 value of the trend line of each scatterplot, with the highest R^2 value representing the graph yielding the most accurate Weibull parameters (**Figure 3.2**).

$$\ln\left(\ln\left(\frac{1}{1 - CDF}\right)\right) \quad \textit{Equation 5}$$

$$\ln(RSL - t_o) \quad \textit{Equation 6}$$

For instance, the highest R^2 for NDDOT's BOB substrate overlaid with chip seals was found to be the plot for $t_o = 0$, with $R^2 = 0.9967$ and the equation for this trend line is ***Equation 7***. The reliability parameters can be obtained from this trend line. The slope is the value of β (2.9122) and together with the t_o (0) and intercept values (-6.5173), μ can be computed using ***Equation 8*** (Izevbekhai, 2014). μ or RSL in this analysis is the service life enhancement since the time of intervention.

$$y = 2.9122x - 6.5173 \quad \textit{Equation 7}$$

$$\mu = t_o + e^{\frac{-int}{\beta}} \quad \textit{Equation 8}$$

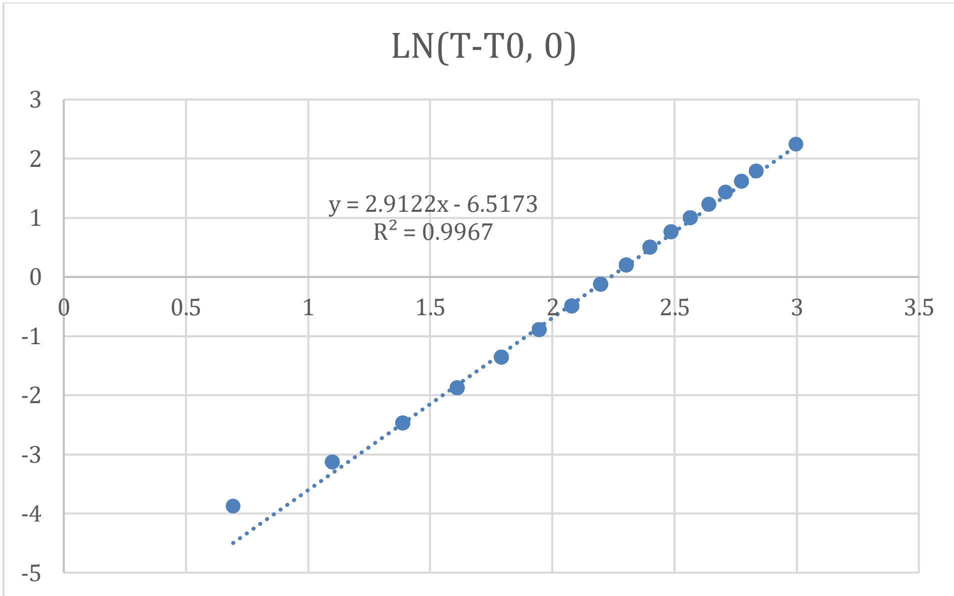

Figure 3.2 An example of plot with the highest R^2 value containing the Weibull parameter.

3.2 T-TEST ANALYSIS

"A t-test is a type of inferential statistic used to determine if there is a significant difference between the means of two groups, which may be related in certain features" (Kenton, 2019). Three key data values used in a t-test are the difference between the mean values from each data set (also known as the mean difference), the standard deviation of each group, and the number of data values of each group.

A correlated or paired t-test was not applicable since this test can only be conducted when the samples have a similar amount of data values. In this case the amount of data values obtained from MnDOT and NDDOT is distinctly nonidentical. Equal variance or pooled t-test and unequal variance t-test were employed to compare the data sets from MnDOT and NDDOT.

F-test was first conducted to determine if each pair of data sets have equal variances, followed by performing equal variance and unequal variance t-tests depending on the results from the F-test.

3.2.1 Equal Variance (or Pooled) T-Test

An equal variance t-test is selected to be used when the datasets fulfill one of the following criteria (Kenton, 2019).

- Number of samples in each dataset is equal
- Variances of the datasets are relatively close to one another

An F-test was performed to compare the variances, which only the data of BAB substrates overlaid with chip seals have equal variances between the two agencies. ***Equation 9*** and ***Equation 10*** are the formulas for computing t-value and degrees of freedom respectively.

$$T - value = \frac{mean1 - mean2}{\sqrt{\frac{(n1-1) \times var1^2 + (n2-1) \times var2^2}{n1 + n2 - 2}} \times \sqrt{\frac{1}{n1} + \frac{1}{n2}}} \quad \textbf{Equation 9}$$

$$Degrees\ of\ freedom = n1 + n2 - 2 \quad \textbf{Equation 10}$$

Where $mean1$ and $mean2$ are the average values of each of the sample sets; $var1$ and $var2$ are the variance of each of the sample sets; and $n1$ and $n2$ are the number of records in each sample set.

3.2.2 Unequal Variance (or Welch's) T-Test

Unequal variance t-test is chosen to be used when the datasets have different number of samples as well as different variances (Kenton, 2019).

The F-test was performed to compare the variances, which all but the data of BAB substrates overlaid with chip seals have unequal variances between the two agencies. ***Equation 11*** and ***Equation 12*** are the formulas for computing t-value and degrees of freedom respectively.

$$T - value = \frac{mean1 - mean2}{\sqrt{\frac{var1^2}{n1} + \frac{var2^2}{n2}}} \quad \textbf{Equation 11}$$

$$Degrees\ of\ freedom = \frac{(\frac{var1^2}{n1} + \frac{var2^2}{n2})^2}{\frac{(\frac{var1^2}{n1})^2}{n1 - 1} + \frac{(\frac{var2^2}{n2})^2}{n2 - 1}} \quad \textbf{Equation 12}$$

Where $mean1$ and $mean2$ are the average values of each of the sample sets; $var1$ and $var2$ are the variance of each of the sample sets; and $n1$ and $n2$ are the number of records in each sample set.

CHAPTER 4: RESULTS

4.1 F-TEST AND T-TEST ANALYSIS

4.1.1 BAB Substrates Overlaid with Chip Seals

F-test was conducted to evaluate if the BAB substrates overlaid with chip seals datasets from MnDOT and NDDOT have equal variances. The null hypothesis used is "variances from the two datasets are equal." **Table 4.1** showed the F-test results obtained using Excel.

Table 4.1 F-test two sample for variances.

	Variable 1	*Variable 2*
Mean	9.031	7.667
Variance	19.23	19.19
Observations	459	24
df	458	23
F	1.002	
P(F<=f) one-tail	0.5338	
F Critical one-tail	1.772	

F value is lower than F critical value as shown in **Table 4.1**, thus the null hypothesis is accepted. MnDOT and NDDOT datasets have equal variances. Hence, equal variance t-test was selected to determine if there is a significant difference between the means of MnDOT and NDDOT datasets. The null hypothesis used is "means from the two datasets do not differ significantly." **Table 4.2** showed the t-test results obtained using Excel.

Table 4.2 T-test: two-sample assuming equal variances.

	Variable 1	*Variable 2*
Mean	9.031	7.667
Variance	19.23	19.19
Observations	459	24
Pooled Variance	19.22	
Hypothesized Mean Difference	0	
df	481	
t Stat	1.486	
P(T<=t) one-tail	0.06903	
t Critical one-tail	1.648	
P(T<=t) two-tail	0.1381	
t Critical two-tail	1.965	

t Stat is between - t Critical two-tail and t Critical two-tail as shown in **Table 4.2**, thus the null hypothesis is accepted. The means of the MnDOT and NDDOT datasets (BAB substrates overlaid with chip seals) do not differ significantly.

4.1.2 BOB Substrates Overlaid with Chip Seals

F-test was performed to evaluate if the BOB substrates overlaid with chip seals datasets from MnDOT and NDDOT have equal variances. The null hypothesis used is "variances from the two datasets are equal." **Table 4.3** showed the F-test results obtained using Excel.

Table 4.3 F-test two sample for variances.

	Variable 1	*Variable 2*
Mean	8.582	8.314
Variance	12.57	9.556
Observations	2263	204
df	2262	203
F	1.315	
P(F<=f) one-tail	0.005948	
F Critical one-tail	1.195	

F value is higher than F critical value as shown in **Table 4.3**, thus the null hypothesis is rejected. MnDOT and NDDOT datasets have unequal variances. Hence, unequal variance t-test was selected to determine if there is a significant difference between the means of MnDOT and NDDOT datasets. The null hypothesis used is "means from the two datasets do not differ significantly." **Table 4.4** showed the t-test results obtained using Excel.

Table 4.4 T-test: two-sample assuming equal variances.

	Variable 1	*Variable 2*
Mean	8.582	8.314
Variance	12.57	9.556
Observations	2263	204
Hypothesized Mean Difference	0	
df	254	
t Stat	1.170	
P(T<=t) one-tail	0.1216	
t Critical one-tail	1.651	
P(T<=t) two-tail	0.2431	
t Critical two-tail	1.969	

t Stat is between - t Critical two-tail and t Critical two-tail as shown in **Table 4.4**, thus the null hypothesis is accepted. The means of the MnDOT and NDDOT datasets (BOB substrates overlaid with chip seals) do not differ significantly.

4.1.3 BAB Substrates Overlaid with Micro-Surfacing

F-test was performed to evaluate if the BAB substrates overlaid with micro-surfacing datasets from MnDOT and NDDOT have equal variances. The null hypothesis used is "variances from the two datasets are equal." **Table 4.5** showed the F-test results obtained using Excel.

Table 4.5 F-test two sample for variances.

	Variable 1	*Variable 2*
Mean	8.017	7.25
Variance	16.87	5.533
Observations	120	16
df	119	15
F	3.049	
P(F<=f) one-tail	0.008567	
F Critical one-tail	2.114	

F value is higher than F critical value as shown in **Table 4.5**, thus the null hypothesis is rejected. MnDOT and NDDOT datasets have unequal variances. Hence, unequal variance t-test was selected to determine if there is a significant difference between the means of MnDOT and NDDOT datasets. The null hypothesis used is "means from the two datasets do not differ significantly." **Table 4.6** showed the t-test results obtained using Excel.

Table 4.6 T-test: two-sample assuming equal variances.

	Variable 1	*Variable 2*
Mean	8.0167	7.25
Variance	16.87	5.533
Observations	120	16
Hypothesized Mean Difference	0	
df	29	
t Stat	1.099	
P(T<=t) one-tail	0.1404	
t Critical one-tail	1.699	
P(T<=t) two-tail	0.2807	
t Critical two-tail	2.045	

t Stat is between - t Critical two-tail and t Critical two-tail as shown in **Table 4.6**, thus the null hypothesis is accepted. The means of the MnDOT and NDDOT datasets (BAB substrates overlaid with micro-surfacing) do not differ significantly.

4.1.4 BOB Substrates Overlaid with Micro-Surfacing

F-test was performed to evaluate if the BOB substrates overlaid with micro-surfacing datasets from MnDOT and NDDOT have equal variances. The null hypothesis used is “variances from the two datasets are equal.” **Table 4.7** showed the F-test results obtained using Excel.

Table 4.7 F-test two sample for variances.

	Variable 1	*Variable 2*
Mean	9.792	8.898
Variance	26.17	14.66
Observations	48	520
df	47	519
F	1.785	
P(F<=f) one-tail	0.001483	
F Critical one-tail	1.386	

F value is higher than F critical value as shown in **Table 4.7**, thus the null hypothesis is rejected. MnDOT and NDDOT datasets have unequal variances. Hence, unequal variance t-test was selected to determine if there is a significant difference between the means of MnDOT and NDDOT datasets. The null hypothesis used is “means from the two datasets do not differ significantly.” **Table 4.8** showed the t-test results obtained using Excel.

Table 4.8 T-test: two-sample assuming equal variances.

	Variable 1	*Variable 2*
Mean	9.792	8.898
Variance	26.17	14.66
Observations	48	520
Hypothesized Mean Difference	0	
df	52	
t Stat	1.180	
P(T<=t) one-tail	0.1217	
t Critical one-tail	1.675	
P(T<=t) two-tail	0.2433	
t Critical two-tail	2.007	

t Stat is between - t Critical two-tail and t Critical two-tail as shown in **Table 4.8**, thus the null hypothesis is accepted. The means of the MnDOT and NDDOT datasets (BOB substrates overlaid with micro-surfacing) do not differ significantly.

4.1.5 BOC Substrates Overlaid with Micro-Surfacing

F-test was performed to evaluate if the BOC substrates overlaid with micro-surfacing datasets from MnDOT and NDDOT have equal variances. The null hypothesis used is “variances from the two datasets are equal.” **Table 4.9** showed the F-test results obtained using Excel.

Table 4.9 F-test two sample for variances.

	Variable 1	*Variable 2*
Mean	13.58	8.371
Variance	21.93	13.35
Observations	26	186
df	25	185
F	1.643	
P(F<=f) one-tail	0.03405	
F Critical one-tail	1.5657	

F value is higher than F critical value as shown in **Table 4.9**, thus the null hypothesis is rejected. MnDOT and NDDOT datasets have unequal variances. Hence, unequal variance t-test was selected to determine if there is a significant difference between the means of MnDOT and NDDOT datasets. The null hypothesis used is “means from the two datasets do not differ significantly.” **Table 4.10** showed the t-test results obtained using Excel.

Table 4.10 T-test: two-sample assuming equal variances.

	Variable 1	*Variable 2*
Mean	13.58	8.371
Variance	21.93	13.35
Observations	26	186
Hypothesized Mean Difference	0	
df	29	
t Stat	5.441	
P(T<=t) one-tail	3.72E-06	
t Critical one-tail	1.699	
P(T<=t) two-tail	7.45E-06	
t Critical two-tail	2.045	

t Stat is greater than t Critical two-tail as shown in **Table 4.10**, thus the null hypothesis is rejected. The means of the MnDOT and NDDOT datasets (BOC substrates overlaid with micro-surfacing) differ significantly.

4.2 WEIBULL ANALYSIS

4.2.1 Ultra-Thin Bonded Wearing Course (UTBWC)

Based on the pavement management data received, NDDOT does not have any substrates that have been overlaid with UTBWC. Thus, the results included in **Table 4.11** are explicitly from MnDOT.

Table 4.11 Weibull parameters obtained from the analysis for UTBWC.

Type of Substrate	Number of Datasets	Threshold Time to Failure, t_o	Failure Mode, β	Remaining Service Life, μ
BOB	84	0	2.93	13.56
BOC	52	2	1.64	8.65

The threshold time to failure, t_o, is 0 for BOB overlaid with UTBWC, which means the distresses will surface once UTBWC has been placed. As for the application of UTBWC on BOC substrates, the distresses will begin to show after 2 years of treatment.

For both substrates (BOB and BOC), the shape parameters, β, are greater than 1, suggesting the failures are wear-out failures. The RSL or μ is the service life enhancement since the time of intervention. The RSL, μ, of BOB substrates (13.56) is longer than that of BOC substrates (8.65). These values are comparable to the performance period specified in the *MnDOT 2019 Pavement Preservation Manual*, which is 7 to 12 years.

4.2.2 Chip Seals

Table 4.12 summarizes the results of chip seals applied on three flexible substrates investigated (BOB, BOC, and BAB), if available, from both MnDOT and NDDOT. There is no BOC segment overlaid with chip seals based on the pavement management data received from NDDOT.

Table 4.12 Weibull parameters obtained from the analysis for chip seals.

Agency	Type of Substrate	Number of Datasets	Threshold Time to Failure, t_o	Failure Mode, β	Remaining Service Life, μ
NDDOT	BOB	204	0	2.91	9.37
MnDOT	BOB	2263	0	2.39	9.83
NDDOT	BOC	0			
MnDOT	BOC	600	0	2.31	8.81
NDDOT	BAB	24	2	1.39	8.69
MnDOT	BAB	459	0	1.92	10.46

The threshold time to failure, t_o, is 0 for all types of substrates (except BAB for NDDOT) overlaid with chip seals, which indicates the distresses will appear instantly after the application of chip seals. Distresses will begin to show after 2 years of chip seals on BAB substrates in North Dakota. For all substrates, the shape parameters, β, are greater than 1, meaning the distributions model wear-out failures.

The RSL, μ, of BOB substrates for data from both agencies is relatively similar to each other. This was proven through the t-tests conducted, which findings portrayed that there are no significant differences between the mean values of the data sets from MnDOT and NDDOT. These values are higher than the performance period specified in the *MnDOT 2019 Pavement Preservation Manual*, which is 5 to 7 years. Similar to the performance period specified by MnDOT, life extension of a chip seal as stated by Pavement Preservation & Recycling Alliance (PPRA) is up to 5 to 7 years.

4.2.3 Micro-Surfacing

Table 4.13 summarizes the results of micro-surfacing applied on three flexible substrates investigated (BOB, BOC, and BAB) from both MnDOT and NDDOT.

Table 4.13 Weibull parameters obtained from the analysis for micro-surfacing.

Agency	Type of Substrate	Number of Datasets	Threshold Time to Failure, t_o	Failure Mode, β	Remaining Service Life, μ
NDDOT	BOB	48	2	1.39	11.07
MnDOT	BOB	520	0	2.21	10.23
NDDOT	BOC	26	0	3.18	15.17
MnDOT	BOC	186	0	2.29	9.60
NDDOT	BAB	16	0	3.49	8.09
MnDOT	BAB	120	0	1.90	9.28

The threshold time to failure, t_o, is 0 for all types of substrates (except BOB for NDDOT) overlaid with chip seals, denoting the distresses will develop promptly after the application of micro-surfacing. Distresses will begin to show after 2 years of micro-surfacing on BOB substrates in North Dakota.

For all substrates, the shape parameters, β, are greater than 1, signifies wear-out failures. The RSL, μ, of BOB and BAB substrates for data from both agencies are relatively similar to each other. The discrepancy in RSL of BOC substrates are apparent. This was supported by the findings from t-tests, in which the results disclosed that the mean values of the two samples differ significantly. These RSLs determined are higher than the performance period specified in the *MnDOT 2019 Pavement Preservation Manual*, which is 5 to 7 years. The life extension as specified by PPRA is 6 to 8 years or more when applied for optimum preservation performance.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

The RSL – service life enhancement since intervention – for all treatments from two agencies (MnDOT and NDDOT) appear to be relatively close to each other, except for the BOC substrates overlaid with micro-surfacing (**Table 5.1**). However, this could be explained through the t-tests performed on BOC substrates overlaid with micro-surfacing data sets, in which results showed the observed difference between the sample is convincing enough to say that the two data sets (MnDOT and NDDOT) differ significantly.

Table 5.1 Weibull parameters obtained for various treatments overlaid on different substrates.

Type of Treatment	Type of Substrate	Threshold Time to Failure, t_o	Failure Mode, β	Remaining Service Life, μ
UTBWC	BOB [1]	0	Wear-out failures	13
	BOC [1]	2		8
Chip Seals	BOB	0	Wear-out failures	9
	BOC [1]	0		8
	BAB	0, 2		8 - 10
Micro-surfacing	BOB	0, 2	Wear-out failures	10 - 11
	BOC	0		9 – 15 [2]
	BAB	0		8 - 9

[1] NDDOT does not have substrates that have been overlaid with this type of treatment.

[2] Significant difference observed between two data sets from t-test analysis.

The likelihood of disparities may stem from multiple factors, such as an insufficient amount of data points and limitations in performance data that lead to reduced accuracy in the estimation of remaining service life, etc.

Regardless of substrate types, UTBWC has an RSL of 8 to 13 years; chip seals have an RSL of 8 to 10 years; micro-surfacing has an RSL of 8 to 11 years (excluding BOC data, which showed significant disparity between the means of the two data sets from t-test analysis). All treatments have a pattern of wear-out failures, which are an indication that the treatments are effective in providing life extensions as the cause of failures is not random.

The RSLs of chip seals and micro-surfacing computed from the analysis are higher than that specified by the agency and industry. This assumes the intervention happens within the optimal timeframe; while the performance period provided by the agency and industry may be more conservative as not all intervention will be optimal, and there are other contingencies to be considered.

Some of the interventions are second or third, and these collectively synergistically improve service life of the substrate. It is recommended that further investigations be conducted to distinguish the performance of segments with single intervention from the performance of segments with additional interventions. This effort will address the overarching and undergirding concerns. Additional data from other state members would improve the system in predicting pavement performance and an update on these existing data (MnDOT and NDDOT) in five years would enhance the performance curves and improve the accuracy of estimated remaining service life.

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