TASK 5 TECHNICAL MEMORANDUM

submitted to the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
(NCHRP)

Project: **10-82 Performance-Related Specifications for Pavement Preservation Treatments**

LIMITED USE DOCUMENT

This document is furnished only for review by members of the NCHRP project panel and is regarded as fully privileged. Dissemination of information included herein must be approved by the NCHRP.

Submitted by
Texas A&M Research Foundation
on behalf of
Texas Transportation Institute & Texas A&M University System
College Station, Texas

October 6, 2011

Subtask 5.1 – Evaluate and Rank Treatments for Suitability for PRS

The criteria for evaluating the suitability of treatments for performance-related specifications (PRS) stem from the definition of PRS. The literature defines PRS as quality assurance specifications that are based on materials and construction acceptance quality characteristics (AQCs) that have been found to correlate with future performance (TRB 2009). Thus, a treatment was deemed suitable for PRS if there is evidence (empirical or mechanistic) that the treatment's in-service performance is correlated with its initial quality.

Empirical evidence of correlation between initial quality and in-service performance was investigated by performing canonical correlation analysis (CCA) (a well-established statistical analysis procedure) on data extracted from the Long-Term Pavement Performance (LTPP) database. Preservation treatments that show significant statistical correlation between initial materials and construction properties (MCPs) and in-service performance were identified as suitable for PRS. The MCPs used in this analysis have three primary characteristics: 1) available in the LTPP database, 2) can be measured at the time of construction, and 3) can be controlled by the contractor or material supplier.

For treatments that do not have sufficient LTPP data, the literature was searched for mechanistic and laboratory evidence of correlation between initial quality and in-service performance. Finally, the research team ranked the treatments that were found to be suitable for PRS to select six treatments recommended for consideration in the PRS guide.

Overview of Data and Canonical Correlation Analysis

Data on the initial quality and in-service performance of 835 LTPP sections for 12 preservation treatments were extracted and analyzed. These treatments are:

- Hot-Mix Asphalt (HMA)-Surfaced Pavement.
    - Thin HMA overlay (58 sections).
    - Chip seals (68 sections).
    - Slurry seals (86 sections).
    - Crack sealing (55 sections).
    - Hot in-place recycling (97 sections).
- Portland Cement Concrete (PCC)-Surfaced Pavement.
    - Joint resealing (136 sections).
    - PCC crack sealing (160 sections).
    - Diamond grinding (37 sections).
    - Dowel bar retrofitting (68 sections).
    - Partial-depth repair (33 sections).
    - Slab stabilization (Undersealing) (15 sections).
    - Full-depth repair (34 sections).

While the LTPP data are not perfect, they have several advantages that made them suitable for this study, including:

- Availability of detailed data on both initial quality of treatments and in-service performance of treated pavement.
- National (i.e., the data are not limited to a particular locality).

- Subject to a formal quality control process.
- Widely used in past national research studies.
- Publicly available.

For HMA treatments, performance is measured in terms of cracking, rutting, and surface roughness. Longitudinal and transverse cracking were summed and are referred to as “cracking.” Fatigue cracking was not included in this analysis as it is a manifestation of structural problems that cannot be corrected with preservation treatments. Roughness is measured in terms of the International Roughness Index (IRI). For PCC treatments, performance is measured in terms of faulting, spalling, and IRI. Spalling is measured as the total number of spalls of different severity levels per section (i.e., if multiple spalls of the same severity level exist in a joint, they are counted as one spall). Since performance data are not available for every year and every pavement section in the LTPP database, average values were computed for 2- or 3-year periods. For instance, cracking data for chip-sealed sections were averaged within each age group of 1–3 years, 4–6 years, and 7–9 years. The LTPP database has limited performance data for pavements age beyond nine years. Therefore, only the first nine years of performance data (grouped into three age groups) are used in this analysis.

For each treatment type and performance indicator, the CCA determines the correlation between the performance variables (e.g., cracking at age groups 1–3 years, 4–6 years, and 7–9 years) and the MCPs. CCA finds pattern(s) that maximize the correlation between the linear combinations of the performance variables and the MCPs. The linear combinations of the MCPs (denoted as *X*) and performance indicator at the three age groups (denoted as *Y*) are called canonical variates and are computed as follows:

$$X_i = a_1 x_{1i} + a_2 x_{2i} + \ldots + a_p x_{pi}$$
$$Y_i = b_1 y_{1i} + b_2 y_{2i} + \ldots + b_q y_{qi}$$

where,

p = the number of MCPs.
q = the number of age groups for the performance indicator under consideration (in this study q = 3).
i = a counter for pavement sections (In this study, *i* loops from 1 to n, where *n* is the total number of pavement sections in the dataset.).
a_1 , a_2, …, a_p = the weight coefficients for the MCPs.
b_1, b_2, …, b_q = the weight coefficients for the performance indicator at age groups 1 to q.

A pair of X_i and Y_i refers to the pair of canonical variates for the *ith* pavement section. CCA chooses weight coefficients from infinite number of possible linear combinations such that the resultant linear combination of the *x* set of variables (i.e., X) is maximally correlated with the linear combinations of the *y* set of variables (i.e., Y) (Levine, 1977). These model coefficients are explained in terms of standard deviation, not the measurement unit of individual variables. For example, a −0.133 model coefficient for thin overlay thickness is interpreted as one standard deviation increase in overlay thickness leads to a 0.133 standard deviation decrease in the MCPs canonical variate (i.e., X), while holding the other MCPs constant.

A significance level of 0.05 was used in this analysis; thus only canonical correlations with a p-value of less than 0.05 are considered significant. The statistical software "R" was used to conduct this analysis.

The purpose of this statistical analysis is neither to predict treatment performance nor to evaluate the effectiveness of the treatments. Instead, the purpose is to determine if there is statistically significant correlation between the treatment's initial materials and construction properties and its in-service performance. As part of Task 6 of the project (which is scheduled to begin after the completion of Task 5), these key quality characteristics, along with other factors such as traffic loadings, climatic factors, and condition of the existing pavement, will be considered in the development of mechanistic-empirical performance prediction models for each preservation treatment selected for consideration in the PRS guidelines.

Assessing the Suitability of HMA Pavement Preservation Treatments for PRS

1. Thin HMA Overlay

A total of 58 LTPP thin overlay sections were used in this analysis. These sections are located in 29 states and four Canadian provinces. Tables 1 and 2 provide descriptive statistics of the materials and construction properties and the performance indicators of these sections, respectively.

Table 1. Descriptive Statistics of Thin HMA Overlay MCPs Data

MCPs	Mean	Std. Dev.	Min	Max
Overlay thickness, in.	1.11	0.30	0.50	1.90
Percent passing #4 Sieve	64.22	10.90	35.00	97.00
Percent passing #200 Sieve	3.94	1.71	1.00	7.30
Asphalt content, %	5.65	0.79	4.30	8.10
Air voids, %	4.90	1.77	1.30	8.70

Table 2. Descriptive Statistics of Thin HMA Overlay Performance Data

Performance Indicator	Age Group	Mean	Std. Dev.	Min	Max
Cracking[(1)], m	1–3	25.81	49.51	0	220.00
	4–6	74.83	83.76	0	287.00
	7–9	100.39	94.80	0	424.00
Rutting, mm	1–3	0.67	1.07	0	4.00
	4–6	2.30	2.23	0	9.50
	7–9	1.72	1.43	0	5.00
IRI, m/km	1–3	1.28	0.39	0.82	2.69
	4–6	1.32	0.54	0.80	3.79
	7–9	1.46	0.52	0.80	3.11

(1) Total longitudinal and transverse cracking

Of the 58 thin overlay sections used in the CCA, 52 sections were used in the cracking analysis, 31 sections were used in the rutting analysis, and 43 sections were used in the IRI analysis. As shown in Table 3, two significant canonical correlations were found between the MCPs and cracking, but no significant correlation was found between thin overlay MCPs and IRI or rutting. The significance of each MCP's influence on the quality-performance correlation was determined based on the value of the canonical loading coefficient. Gebers and Peck (2003) noted that for the variables (i.e., MCPs in this case) to have meaningful influence on the canonical correlations, the loading coefficient should have an absolute value of 0.30 or higher. Yes in Table 4 indicates that the loading coefficient for the MCP and corresponding performance indicator has an absolute value of at least 0.3; and thus the MCP has meaningful influence on the quality-performance correlation. No results are provided for rutting and IRI because no significant canonical correlations were found between the MCPs and these performance indicators.

Table 3. Thin HMA Overlay Canonical Correlations and Test of Significance

Performance Indicator	No. of Obs	Canonical Correlation	Wilks' L	F	df1	df2	p-value
Cracking	52	0.74	0.315	4.218	15	121.9	3.12E-06
		0.50	0.695	2.243	8	90	0.0312
Rutting	31	Insignificant	-	-	-	-	-
IRI	43	Insignificant	-	-	-	-	-

Table 4. Influence of Thin HMA Overlay MCPs on the Quality-Performance Correlation (Yes=Significant, No=Not Significant, N/A=Not Applicable)

MCPs	Cracking	Rutting	IRI
Overlay thickness, in.	Yes	N/A	N/A
Percent passing #4 Sieve	Yes	N/A	N/A
Percent passing #200 Sieve	Yes	N/A	N/A
Percent asphalt content	Yes	N/A	N/A
Percent air voids	Yes	N/A	N/A

Table 5 presents the standardized coefficients for the most significant canonical models (i.e., models with the highest canonical correlation coefficient) that relate the MCPs of thin HMA overlays to pavement performance. These model coefficients are used for computing the X and Y variates (see X and Y in Figure 1). Figure 1 shows a scatter plot of the canonical variates for thin overlay sections with complete data (i.e., with data on all MCPs and on cracking at all age groups 1–3, 4–6, and 7–9 years). The X in this plot represents a standardized linear combination of the MCPs affecting cracking, and the Y represents the corresponding standardized linear combination of cracking at 1–3, 4–6, and 7–9 years. Note that sections with missing data on any of the MCPs or on cracking at any age group are not shown in this plot.

The correlation between initial quality of thin HMA overlay (represented by overlay thickness, percent passing #4 sieve, percent passing #200 sieve, asphalt content, and air voids) and cracking suggests that thin HMA overlay is suitable for PRS on the basis of cracking. The lack of correlation between these initial quality characteristics and rutting and IRI may be an indicator that other factors (such as the underlying pavement, traffic loadings, and other site factors) have greater influence on rutting and IRI than the initial quality of the thin overlay (at least in the dataset used in this analysis).

Table 5. Coefficients of Thin HMA Overlay Canonical Correlation Models

Variables	Cracking Model Coefficients	Rutting Model Coefficients	IRI Model Coefficients
MCPs (X_i):			
Overlay thickness, in.	−0.133	N/A	N/A
Percent passing #4 Sieve	−1.060	N/A	N/A
Percent passing #200 Sieve	0.660	N/A	N/A
Percent asphalt content	0.243	N/A	N/A
Percent air voids	−0.307	N/A	N/A
Performance (Y_i):			
Performance at age 1–3 years	1.180	N/A	N/A
Performance at age 4–6	−2.089	N/A	N/A
Performance at age 7–9	1.311	N/A	N/A

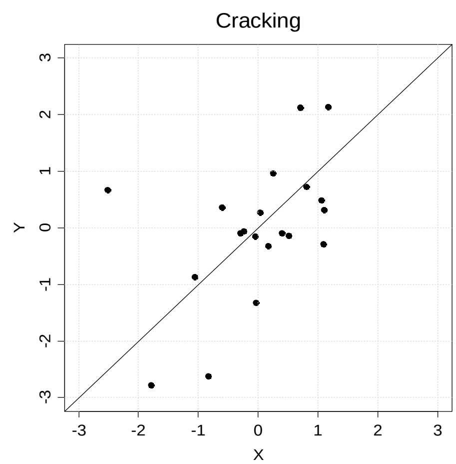


Figure 1 Scatter plot of canonical variates for thin HMA overlay sections: Y=standardized linear combination of cracking at 1–3, 4–6, and 7–9 years; X= standardized linear combination of MCPs.

2. Chip Seal

A total of 68 LTPP chip seal sections were used in this analysis. These sections are located in 29 states and four Canadian provinces. Tables 6 and 7 provide key descriptive statistics for the materials and construction properties and the performance indicators of these sections, respectively. Of the 68 chip seal sections used in the CCA, 62 sections were used in the cracking analysis, 38 sections were used in the rutting analysis, and 58 sections were used in the IRI analysis.

Table 6. Descriptive Statistics of Chip Seal MCPs Data

MCPs	Mean	Std. Dev.	Min	Max
Asphalt application rate ratio (1)	1.00	0.07	0.82	1.15
Aggregate application rate ratio (1)	1.07	0.19	0.00	1.46
Flakiness index	12.47	2.95	7.00	21.00
Percent passing #4 sieve	5.25	9.24	1.00	54.00
Percent Passing #200 sieve	0.78	0.44	0.00	1.90
Percent cracking sealed	38.54	43.00	0.00	100.00
Penetration, 0.1 mm	119.78	48.45	32.00	216.00
Viscosity at 50°C, s	127.96	65.25	23.00	321.00

(1) Application rate ratio = actual application rate/target application rate

Table 7. Descriptive Statistics of Chip Seal Performance Data

Performance Indicator	Age	Mean	Std. Dev.	Min	Max
Cracking, m	1–3	55.55	79.71	0	396.00
	4–6	97.26	114.19	0	383.00
	7–9	76.91	111.69	0	374.00
Rutting, mm	1–3	5.04	3.85	1.00	16.00
	4–6	5.96	4.29	0	16.00
	7–9	7.62	4.84	0	19.00
IRI, m/km	1–3	1.39	0.46	0.68	2.87
	4–6	1.51	0.54	0.64	3.23
	7–9	1.69	0.74	0.62	4.02

As shown in Table 8, significant canonical correlations were found between chip seal MCPs and all three performance indicators (cracking, rutting, and IRI). Table 9 shows the influence of the MCPs on the quality-performance correlations. Yes in this table indicates that the loading coefficient for the MCP, and corresponding performance indicator has an absolute value of at least 0.3; and thus the MCP has meaningful influence on the quality-performance correlation. As discussed earlier the 0.3 threshold value was obtained from Gebers and Peck (2003).

Table 8. Chip Seal Canonical Correlations and Test of Significance

Performance Indicator	No. of Obs	Canonical Correlation	Wilks' L	F	df1	df2	p-value
Cracking	62	0.75	0.289	3.311	24	148.5	4.19E-06
Rutting	38	0.67	0.416	2.279	14	58	0.0147
IRI	58	0.54	0.634	2.088	12	98	0.0244

Table 9. Influence of Chip Seal MCPs on the Quality-Performance Correlation (Yes=Significant, No=Not Significant, N/A=Not Applicable)

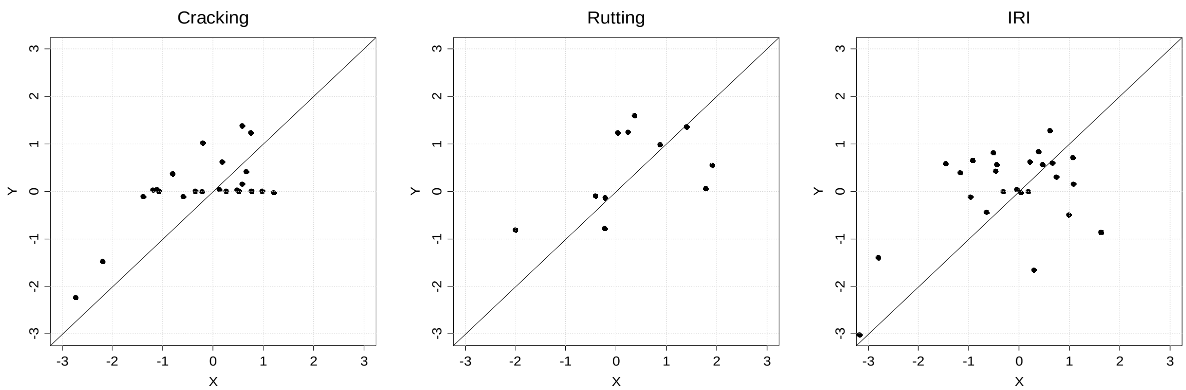
MCPs	Cracking	Rutting	IRI
Asphalt application rate ratio	Yes	No	Yes
Aggregate application rate ratio	Yes	No	No
Flakiness index	Yes	Yes	Yes
Percent passing #4 sieve	Yes	Yes	Yes
Percent passing #200 sieve	Yes	No	No
Percent cracking sealed	No	No	N/A
Penetration, 0.1 mm	No	No	Yes
Viscosity at 50°C, s	Yes	Yes	Yes

Table 10 presents the standardized coefficients for the most significant canonical models (i.e., models with the highest canonical correlation coefficient) that relate the MCPs of chip seal to pavement performance. These model coefficients are used for computing the X and Y variates (see X and Y in Figure 2). Figure 2 shows a scatter plot of the canonical variates for chip seal sections with complete data. The X in this plot represents a standardized linear combination of the MCPs affecting cracking, rutting, and IRI, and the Y represents the corresponding standardized linear combination of cracking, rutting, and IRI at 1–3, 4–6, and 7–9 years.

The CCA results suggest that initial quality of chip seal correlates with cracking, rutting, and IRI in the treated pavement; and thus chip seal is suitable for PRS. The data suggest that flakiness index, percent passing #4 sieve, and asphalt viscosity correlate with all three performance indicators. Other properties (asphalt application rate ratio, aggregate application rate ratio, percent passing #200 sieve, and asphalt penetration) correlate with at least one of the three performance indicators.

Table 10. Coefficients of Chip Seal Canonical Correlation Models

Variables	Cracking Model Coefficients	Rutting Model Coefficients	IRI Model Coefficients
MCPs (X_i):			
Asphalt application rate ratio	−0.373	−0.032	−0.331
Aggregate application rate ratio	−0.255	−0.043	−0.197
Flakiness index	−0.432	−0.416	−0.102
Percent passing #4 sieve	−0.414	0.402	−0.577
Percent passing #200 sieve	−0.477	−0.142	−0.275
Percent cracking sealed	0.214	−0.259	0.331
Penetration, 0.1 mm	−0.168	0.328	−0.453
Viscosity at 50°C, s	−0.364	0.774	−0.331
Performance (Y_i):			
Age 1–3	−0.814	−2.594	1.177
Age 4–6	−0.481	3.035	−2.324
Age 7–9	1.402	−0.008	0.297



(a) (b) (c)

Figure 2. Scatter plot of canonical variates for chip seal sections, where Y=standardized linear combination of performance indicator at age groups 1–3, 4–6, and 7–9 years; X= standardized linear combination of MCPs affecting performance: (a) Cracking; (b) Rutting; (c) IRI.

3. Slurry Seal

A total of 86 LTPP slurry seal sections were used in this analysis. These sections are located in 29 states and four Canadian provinces. Tables 11 and 12 provide key descriptive statistics for the materials and construction properties and the performance indicators of these sections, respectively. Of the 86 slurry seal sections used in the CCA, 84 sections were used in the cracking analysis, 42 sections were used in the rutting analysis, and 60 sections were used in the IRI analysis.

Table 11. Descriptive Statistics of Slurry Seal MCPs Data

MCPs	Mean	Std. Dev.	Min	Max
Penetration, 0.1 mm	64.45	21.77	31.00	157.00
Viscosity at 25°C, s	19.15	3.54	7.00	29.00
Percent passing #4 sieve	86.04	4.12	77.00	94.00
Percent passing #200 sieve	10.65	1.33	7.00	15.00
Slurry application rate ratio (1)	1.01	0.13	0.79	1.41
Percent cracks sealed prior to applying slurry seal	36.22	42.07	0.00	100. 0

(1) *Application rate ratio = actual application rate/target application rate; Application rate in pounds of dry aggregate per square yard.*

Table 12. Descriptive Statistics of Slurry Seal Performance Data

Performance Indicator	Age Group	Mean	Std. Dev.	Min	Max
	1–3	67.16	88.00	0	373.00
Cracking, m	4–6	118.80	117.10	0	414.50
	7–9	134.85	131.49	0	528.00
	1–3	5.08	3.39	1.00	15.67
Rutting, mm	4–6	5.78	3.56	1.00	16.00
	7–9	5.75	2.75	1.00	10.00
	1–3	1.39	0.53	0.70	3.38
IRI, m/km	4–6	1.51	0.64	0.67	4.12
	7–9	1.74	0.77	0.74	3.77

As shown in Table 13, two significant canonical correlations were found between slurry seal MCPs and cracking, one canonical correlation was found between these MCPs and IRI, but no significant correlation was found between slurry seal MCPs and rutting. Table 14 shows the influence of slurry seal MCPs on the quality-performance correlations. Yes in this table indicates that the MCP has meaningful influence on the quality-performance correlation. No results are provided for rutting because no significant canonical correlation between these MCPs and rutting was found.

Table 13. Slurry Seal Canonical Correlations and Test of Significance

Performance Indicator	No. of Obs	Canonical Correlation	Wilks' L	F	df1	df2	p-value
Cracking	84	0.65	0.346	4.535	21	213	3.6E-09
		0.59	0.593	3.737	12	150	5.94E-05
Rutting	42	Insignificant	-	-	-	-	-
IRI	60	0.84	0.229	5.504	18	145	1.08E-09

Table 14. Influence of Slurry Seal MCPs on the Quality-Performance Correlation
(Yes=Significant, No=Not Significant, N/A=Not Applicable)

MCPs	Cracking	Rutting	IRI
Penetration, 0.1 mm	Yes	N/A	Yes
Viscosity at 25°C, s	Yes	N/A	No
Percent passing #4 sieve	Yes	N/A	Yes
Percent passing #200 sieve	No	N/A	Yes
Aggregate moisture	Yes	N/A	Yes
Slurry application rate ratio	Yes	N/A	Yes
Percent cracks sealed prior to applying slurry seal	Yes	N/A	N/A

Table 15 presents the standardized coefficients for the most significant canonical models that relate the MCPs of slurry seal to pavement performance. These model coefficients are used for computing the X and Y variates (see X and Y in Figure 3). Figure 3 shows a scatter plot of the canonical variates for slurry sections with complete data. The X in these plots represents a standardized linear combination of the MCPs affecting performance, and the Y represents the corresponding standardized linear combinations of cracking and IRI at 1–3, 4–6, and 7–9 years.

The CCA results provides empirical evidence that there is meaningful correlation between the initial quality of slurry seal (represented by asphalt penetration and viscosity, percent passing #4 sieve, percent passing #200 sieve, aggregate moisture, slurry application rate ratio, and percent cracks sealed prior to applying slurry seal) and cracking and IRI of the treated pavement. Thus, slurry seal is considered suitable for PRS on the basis of cracking and IRI.

The finding that slurry seal is suitable for PRS can be extended to microsurfacing. The literature suggests that microsurfacing is essentially a technologically improved version of slurry seal (e.g., Morian 2011, Gransberg 2010, Smith and Beatty 1999). The improvements normally include the use of a modified binder and set control agents that reduce the required cure time and allow for early opening to traffic. Microsurfacing application process and equipment are similar to those used for slurry seal (Morian 2011). NCHRP Synthesis 411 on microsurfacing found that most state DOT specifications included microsurfacing and slurry seal together in the same specifications section, many times with little or no differentiation between the two treatments (Gransberg 2010).

Table 15. Coefficients of Slurry Seal Canonical Correlation Models

Variables	Cracking Model Coefficients	Rutting Model Coefficients	IRI Model Coefficients
MCPs (X_i):			
Penetration, 0.1 mm	0.150	N/A	0.509
Viscosity at 25°C, s	0.768	N/A	0.322
Percent passing #4 Sieve	−0.421	N/A	−0.528
Percent passing #200 Sieve	−0.027	N/A	0.641
Aggregate moisture	−0.451	N/A	0.322
Slurry application rate ratio	0.035	N/A	−0.136
%Cracks sealed	−0.765	N/A	N/A
Performance (Y_i):			
Age 1–3	0.477	N/A	2.356
Age 4–6	−1.249	N/A	−3.114
Age 7–9	1.520	N/A	1.195

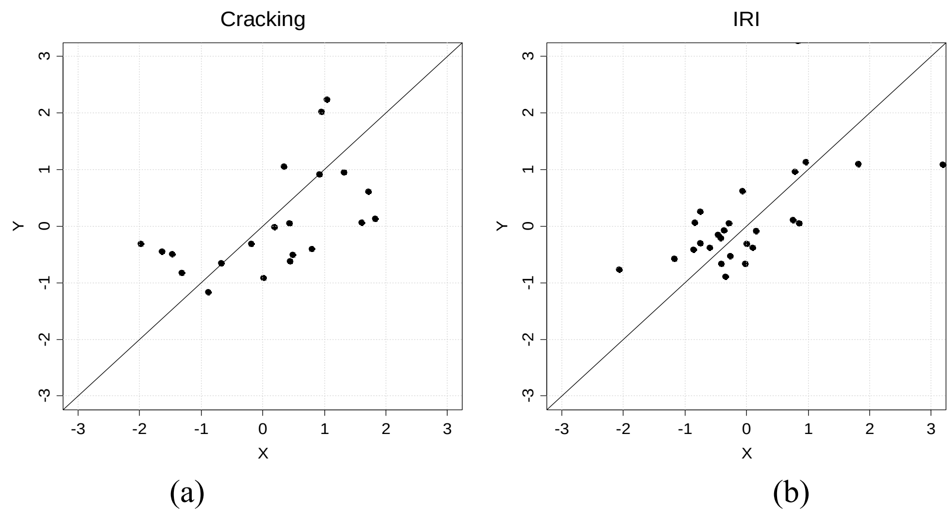


Figure 3. Scatter plot of canonical variates for slurry seal sections, where Y=standardized linear combination of performance indicator at age groups 1–3, 4–6, and 7–9 years; X= standardized linear combination of MCPs affecting performance: (a) Cracking; (b) IRI.

4. Crack Sealing

A total of 55 LTPP crack sealing sections were used in this analysis. These sections are located in 28 states and four Canadian provinces. Tables 16 and 17 provide key descriptive statistics for the materials and construction properties and the performance indicators of these sections, respectively. Of the 55 crack sealing sections used in the CCA, 45 sections were used in the cracking analysis, 30 sections were used in the rutting analysis, and 51 sections were used in the IRI analysis.

Table 16. Descriptive Statistics for Crack Sealing MCPs

MCPs	Mean	Std. Dev.	Min	Max
Avg. width of prepared crack, in.	1.16	0.50	0.12	1.55
Avg. depth of prepared crack, in.	0.76	1.47	0.10	9.99
Avg. sealant temperature(1), °F	377.46	12.89	349.00	405.00
Avg. width of completed sealed crack, in.	1.95	0.87	0.80	3.40
Avg. sealant thickness(2), in.	0.26	0.13	0.03	0.50

(1) Average temperature of the sealant in the applicator (from beginning to end of a sealing operation)
(2) Average thickness of sealant above or below pavement surface (>0 if overfilled; <0 if recessed; =0 if level with the surface)

Table 17. Descriptive Statistics for Performance Indicators of Crack-Sealed Pavements

Performance Indicator	Age Group	Mean	Std. Dev.	Min	Max
Cracking, m	1–2	146.04	120.04	0	493.0
	3–4	169.05	136.16	0	421.0
	5–6	201.21	164.60	0	597.0
Rutting, mm	1–2	5.71	3.87	0.50	16.00
	3–4	6.36	4.29	1.00	18.00
	5–6	7.30	5.20	1.00	21.00
IRI, m/km	1–2	1.47	0.64	0.65	3.47
	3–4	1.53	0.71	0.63	3.71
	5–6	1.56	0.55	0.80	3.41

As shown in Table 18, significant canonical correlations were found between crack sealing MCPs and each performance indicator (cracking, rutting, and IRI). Table 19 shows whether each MCP has significant influence on the quality-performance correlations.

Table 18. Crack Sealing Canonical Correlation and Test of Significance

Performance Indicator	No. of Obs	Canonical Correlation	Wilks' L	F	df1	df2	p-value
Cracking, m	45	0.995	0.008	32.536	15	103	3.37E-32
Rutting, mm	30	0.75	0.357	1.846	15	61.1	0.0481
IRI, m/km	51	0.72	0.396	3.161	15	119.1	0.0002

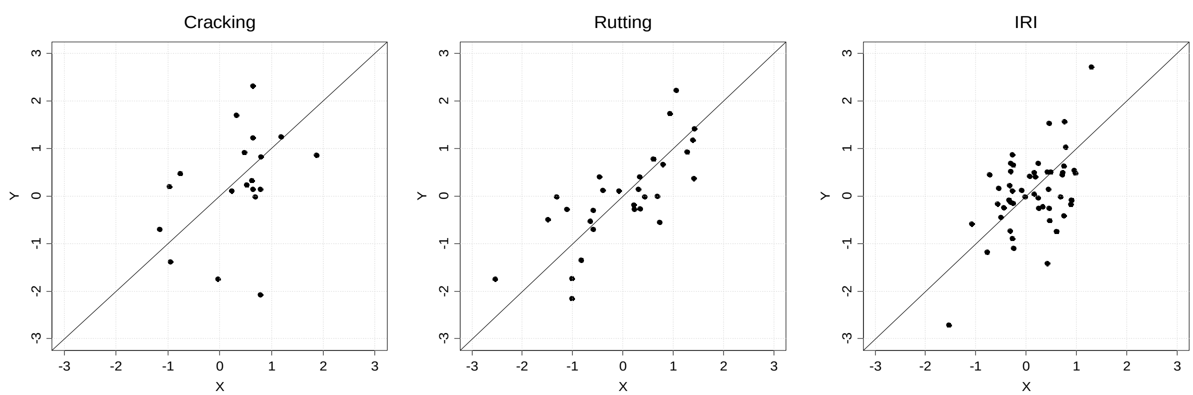
Table 19. Influence of Crack Sealing MCPs on the Quality-Performance Correlation (Yes=Significant, No=Not Significant, N/A=Not Applicable)

MCPs	Cracking	Rutting	IRI
Avg. width of prepared crack, in.	No	No	No
Avg. depth of prepared crack, in.	No	Yes	Yes
Avg. sealant temperature, °F	No	Yes	No
Avg. width of completed crack, in.	Yes	Yes	No
Avg. sealant thickness above or below pavement surface, in.	Yes	Yes	No

Table 20 presents the standardized coefficients for the canonical models that relate crack sealing MCPs to performance, which were then used for computing canonical variates (X and Y in Figure 4). Figure 4 shows a scatter plot of the canonical variates for crack sealing sections with complete data. The X in these plots represents a standardized linear combination of the MCPs affecting performance, and the Y represents the corresponding standardized linear combination of the performance indicators at age groups 1–3, 4–6, and 7–9 years.

Table 20. Coefficients of Crack Sealing Canonical Correlation Models

Variables	**Cracking Model Coefficients**	**Rutting Model Coefficients**	**IRI Model Coefficients**
MCPs (X_i):			
Avg. width of prepared crack, in.	0.108	0.417	0.224
Avg. depth of prepared crack, in.	0.092	−0.589	−0.904
Avg. sealant temperature, °F.	−0.132	0.322	−0.691
Avg. width of completed crack, in.	0.960	−0.705	−0.080
Avg. sealant thick. above/below surface, in.	0.438	0.585	−0.346
Performance (Y_i):			
Age 1–2	−1.442	−1.080	3.138
Age 3–4	−2.254	−1.103	−2.967
Age 5–6	3.557	2.772	−0.660



(a) (b) (c)

Figure 4. Scatter plot of canonical variates for crack sealing sections, where Y=standardized linear combination of performance indicator at 1–3, 4–6, and 7–9 years; X= standardized linear combination of MCPs affecting performance: (a) Cracking; (b) Rutting; (c) IRI.

The results of the CCA suggest that initial quality of crack sealing is important for the performance of this treatment in terms of cracking, rutting, and IRI. As discussed earlier, these results should not be interpreted as in terms of how effective crack sealing is in slowing cracking, rutting, and IRI. Instead, these results should be interpreted as "crack sealing initial quality correlates well with the performance of crack sealed pavement;" and thus, crack sealing is suitable for PRS.

5. Hot In-Place Recycling

A total of 97 LTPP hot in-place recycling sections were used in this analysis. These sections are located in 24 states and six Canadian provinces. Tables 21 and 22 provide descriptive statistics for the materials and construction properties and the performance indicators of these sections, respectively.

Table 21. Descriptive Statistics for Hot In-Place Recycling MCPs

MCPs	Mean	Std. Dev.	Min	Max
Pavement processed (=1 if yes; =0 otherwise)	0.91*	0.29	0.00	1.00
Percent passing #4 sieve	63.80	9.95	47.00	93.10
Percent passing #200 sieve	6.97	3.13	1.00	14.00
Percent of new asphalt cement added by weight	4.03	1.11	0.80	6.30
Mean bulk specific gravity of as-placed mixture	2.35	0.10	2.14	2.61
Asphalt content	5.13	1.10	3.30	7.80
Percent air voids	4.35	1.61	3.10	16.50

**Mean value represents percent of sections with variable equal to 1.*

Table 22. Descriptive Statistics for Performance Indicators of Hot In-Place Recycled Pavements

Performance Indicator	Age Group	Mean	Std. Dev.	Min	Max
Cracking, m	1–3	25.81	49.51	0	220.00
	4–6	74.83	83.76	0	287.00
	7–9	100.39	94.80	0	424.00
IRI, m/km	1–3	0.90	0.27	0.39	1.73
	4–6	0.94	0.28	0.44	1.87
	7–9	1.02	0.36	0.50	2.03

Of the 97 hot in-place recycling sections used in the CCA, 80 sections were used in the cracking analysis and 85 sections were used in the IRI analysis. The rutting data were insufficient to conduct CCA for rutting. As shown in Table 23, one significant canonical correlation was found between the MCPs of hot in-place recycling and cracking, and three canonical correlations were found between these MCPs and IRI. Table 24 shows whether each MCP has significant influence on the quality-performance correlations. No results are provided for rutting because no CCA was performed due to insufficient rutting data.

Table 23. Hot In-Place Recycling Canonical Correlations and Test of Significance

Performance Indicator	No. of Obs	Canonical Correlation	Wilks' L	F	df1	df2	p-value
Cracking	80	0.65	0.440	3.175	21	202	1.18E-05
Rutting	-	-	-	-	-	-	-
IRI	85	0.77	0.167	8.900	21	216	1.25E-19
		0.69	0.414	7.021	12	152	4.63E-10
		0.47	0.781	4.312	5	77	0.0016

Table 24. Influence of Hot In-Place Recycling MCPs on the Quality-Performance Correlation (Yes=Significant, No=Not Significant, N/A=Not Applicable)

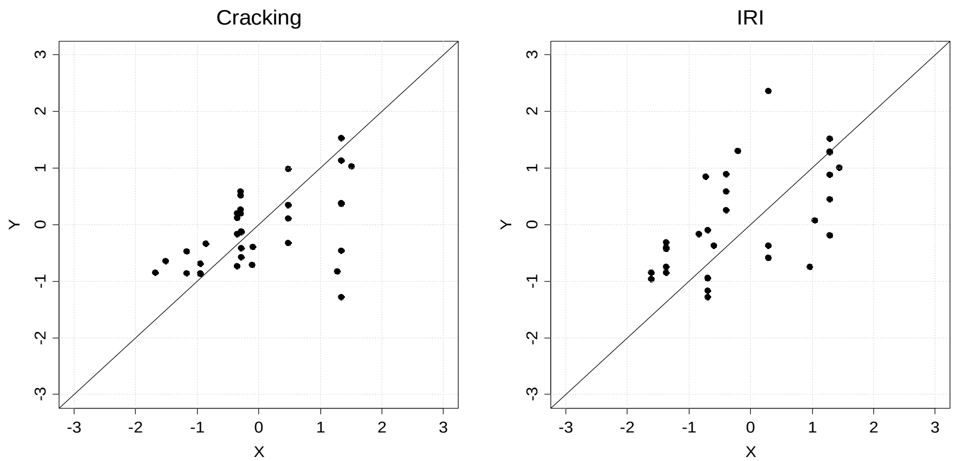
MCPs	Cracking	Rutting	IRI
Pavement processed	No	N/A	Yes
Percent passing #4 sieve	Yes	N/A	Yes
Percent passing #200 sieve	Yes	N/A	Yes
Asphalt amount new	Yes	N/A	Yes
Bulk specific gravity	No	N/A	Yes
Asphalt content	Yes	N/A	Yes
Percent air voids	No	N/A	Yes

Table 25 presents the standardized coefficients for the canonical models that relate the MCPs of hot in-place recycling to performance, which were then used for computing canonical variates (X and Y in Figure 5). Figure 5 shows a scatter plot of the canonical variates for hot in-place recycling sections with complete data.

The CCA results suggest that there is correlation between the initial quality of hot in-place recycling and its in-service performance (cracking and IRI); and thus this treatment can be suitable for PRS. However, the utilization of hot in-place recycling as preservation treatment is limited. A recent survey of highway agencies found that only 10 percent of highway agencies use hot in-place recycling as a preservation treatment (Smith and Peshkin 2011). This fact has lowered the ranking of this treatment for consideration in the PRS guide (see discussion of treatments rankings in later section of this report).

Table 25. Coefficients of Hot In-Place Recycling Canonical Correlation Models

Variables	Cracking Model Coefficients	Rutting Model Coefficients	IRI Model Coefficients
MCPs (X_i):			
Pavement processed	0.170	N/A	−0.876
Percent passing #4 sieve	−1.089	N/A	0.103
Percent passing #200 sieve	−0.101	N/A	0.547
Asphalt amount new	−0.602	N/A	−0.507
Bulk specific gravity	0.007	N/A	−0.403
Asphalt content	0.421	N/A	0.207
Percent air voids	0.502	N/A	−0.369
Performance (Y_i):			
Age 1–3	−0.068	N/A	−0.143
Age 4–6	−0.329	N/A	1.943
Age 7–9	1.138	N/A	−1.522



(a) (b)

Figure 5. Scatter plots of hot in-place recycling canonical variates, where Y=linear combination of performance indicator at ages 1–3, 4–6, and 7–9 years and X= linear combination of MCPs affecting performance: (a) Cracking; (b) IRI.

Assessing the Suitability of PCC Pavement Preservation Treatments for PRS

1. Joint Resealing

A total of 136 LTPP joint resealing sections were used in this analysis. These sections are located in 22 states and two Canadian provinces. Tables 26 and 27 provide descriptive statistics of the materials and construction properties and the performance indicators of these sections, respectively. All 133 joint resealing sections were used in the IRI analysis and 54 sections (of the 133 sections) were used in the faulting analysis. Spalling data were insufficient to conduct CCA for spalling.

Table 26. Descriptive Statistics for Joint Resealing MCPs

MCPs(1)	**Mean**	**Std. Dev.**	**Min**	**Max**
Shape Factor (sealant depth to width ratio)	2.526	1.761	0.000	8.000
Bond break not used(2) (=1 if yes; =0 otherwise)	0.376	0.486	0.000	1.000
Sidewalls not refaced (=1 if yes; =0 otherwise)	0.541	0.500	0.000	1.000
Silicon sealant (=1 if yes; =0 otherwise)	0.205	0.405	0.000	1.000
Hot Pour mix sealant (=1 if yes; =0 otherwise)	0.644	0.481	0.000	1.000
Seal depth(3), in	0.212	0.188	0.000	1.000

(1) For discrete (count) variables, mean value represents percent of sections with variable equal to 1.
(2) Material used to prevent adhesive bonding between the sealant and the bottom of the reservoir.
(3) Seal Depth=Depth from the top of the slab to the top of the joint sealant material, in.

Table 27. Descriptive Statistics for Performance Indicators of Pavements with Resealed Joints

Performance Indicator	Age Group	Mean	Std. Dev.	Min	Max
IRI, m/km	1–3	1.748	0.812	0.730	4.980
	4–6	1.869	0.817	0.720	5.050
	7–9	1.777	0.548	0.750	2.860
Faulting, mm	1–3	1.677	2.149	0.00	11.20
	4–6	1.808	2.008	0.00	8.20
	7–9	2.230	2.419	0.20	11.60
Number of Spalls	1–3	3.614	4.256	0.00	15.00
	4–6	5.738	7.184	0.00	21.67
	7–9	7.103	8.615	0.00	29.50

As shown in Table 28, two significant canonical correlations were found between the MCPs of joint resealing and IRI, and two canonical correlations were found between these MCPs and faulting. In the faulting dataset, the shape factor was very similar for most of the sections, and thus was not included in the faulting analysis. No CCA was performed for spalling due to insufficient data on spalling. Table 29 shows the influence of joint resealing MCPs on the quality-performance correlations. Yes in this table indicates that the loading coefficient for the MCP and corresponding performance indicator has an absolute value of at least 0.3; and thus the MCP has meaningful influence on the quality-performance correlation. As discussed earlier the 0.3 threshold value was obtained from Gebers and Peck (2003).

Table 28. Joint Resealing Canonical Correlations and Test of Significance

Performance Indicator	No. of Obs	Canonical Correlation	Wilks' L	F	df1	df2	p-value
IRI, m/k m	133	0.72	0.311	9.972	18.000	351.210	1.69E-22
		0.58	0.641	6.230	10.000	250.000	1.66E-08
Faulting, mm	54	0.62	0.483	5.162	8.000	94.000	2.38E-05
		0.46	0.789	4.275	3.000	48.000	9.39E-03
Number of Spalls(1)	21	-	-	-	-	-	-

(1) Insufficient data for conducting CCA.

Table 29. Influence of Joint Resealing MCPs on the Quality-Performance Correlation (Yes=Significant, No=Not Significant, N/A=Not Applicable)

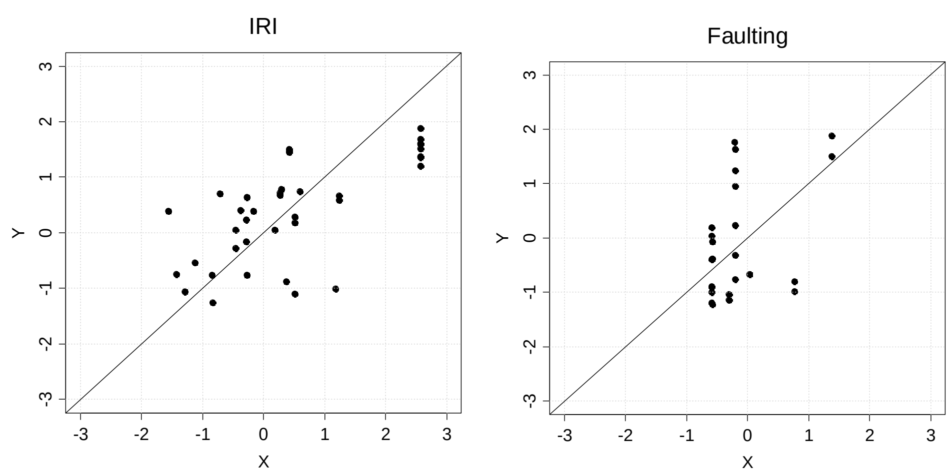
MCPs	IRI	Faulting	Spalling
Shape Factor	Yes	N/A	N/A
Bond break not used	Yes	Yes	N/A
Sidewalls not refaced	Yes	Yes	N/A
Silicon Sealant	Yes	Yes	N/A
Hot Pour Mix Sealant	Yes	Yes	N/A
Seal Depth, inch	Yes	Yes	N/A

Table 30 presents the standardized coefficients for the canonical models that relate the MCPs of joint resealing to pavement performance, which were then used for computing canonical variates (X and Y in Figure 6). Figure 6 shows a scatter plot of the canonical variates for joint resealing sections with complete data.

The CCA results suggest that initial quality of joint resealing (represented by shape factor, use of bond breaker between the sealant and the bottom of the reservoir, refacing of sidewalls, sealant type, and seal depth) correlates with faulting and IRI in the treated pavement; and thus joint resealing is suitable for PRS. The data suggest that refacing of the sidewalls and sealant type correlate with faulting and IRI. The remaining quality characteristics correlate with either faulting or IRI.

Table 30. Coefficients of Joint Resealing Canonical Correlation Models

Variables	IRI Model Coefficients	Faulting Model Coefficients	Spalling Model Coefficients
MCPs (X_i):			
Shape Factor	0.954	N/A	N/A
Bond break not used	−0.147	−0.611	N/A
Sidewalls not refaced	−0.673	0.303	N/A
Silicon Sealant	0.138	−0.423	N/A
Hot Pour Mix Sealant	0.025	0.238	N/A
Seal Depth, inch	−0.209	0.782	N/A
Performance (Y_i):			
Age 1–3	0.485	−1.051	N/A
Age 4–6	−0.915	0.561	N/A
Age 7–9	−0.643	1.626	N/A



(a) (b)

Figure 6. Scatter plots of joint resealing canonical variates, where Y=linear combination of performance indicator at ages 1–3, 4–6, and 7–9 years and X= linear combination of MCPs affecting performance: (a) IRI; (b) Faulting.

2. PCC Crack Sealing

A total of 160 LTPP crack sealing sections were used in this analysis. These sections are located in 20 states and one Canadian province. Tables 31 and 32 provide descriptive statistics of the materials and construction properties and the performance indicators of these sections, respectively. Of the 160 crack sealing sections used in the CCA, 145 sections were used in the IRI analysis, 144 sections were used in the faulting analysis, and 145 sections were used in the spalling analysis.

Table 31. Descriptive Statistics for Crack Sealing MCPs

MCPs(1)	Mean	Std. Dev.	Min	Max
Shape factor (sealant depth to width ratio)	4.177	3.344	0.000	17.670
Silicon sealant (=1 if yes; =0 otherwise)	0.545	0.500	0.000	1.000
Hot pour mix sealant (=1 if yes; =0 otherwise)	0.179	0.385	0.000	1.000
Seal depth(2), in.	0.258	0.192	0.000	1.000

(1) For discrete (count) variables, mean value represents percent of sections with variable equal to 1.
(3) Seal Depth=Depth from the top of the slab to the top of the crack sealant material, in.

Table 32. Descriptive Statistics for Performance Indicators of Pavements with Sealed Cracks

Performance Indicator	Age Group	Mean	Std. Dev.	Min	Max
IRI, m/km	1–3	1.731	0.562	0.780	3.220
	4–6	1.854	0.600	0.860	3.460
	7–9	2.009	0.649	0.840	3.700
Faulting, mm	1–3	0.973	1.342	0.000	11.200
	4–6	0.776	1.178	0.000	6.700
	7–9	1.522	1.854	0.000	11.600
Number of Spalls	1–3	1.864	4.189	0.000	28.500
	4–6	2.424	4.316	0.000	21.000
	7–9	1.410	2.345	0.000	16.000

As shown in Table 33, one significant canonical correlation was found between the MCPs of crack sealing and IRI, two canonical correlations were found between these MCPs and faulting, and one correlation was found between these MCPs and spalling. Table 34 shows the influence of crack sealing MCPs on the quality-performance correlations. Yes in this table indicates that the loading coefficient for the MCP and corresponding performance indicator has an absolute value of at least 0.3; and thus the MCP has meaningful influence on the quality-performance correlation.

Table 33. Crack Sealing Canonical Correlations and Test of Significance

Performance Indicator	No. of Obs	Canonical Correlation	Wilks' L	F	df1	df2	p-value
IRI	145	0.37	0.803	2.633	12.000	365.405	2.178E-03
Faulting	144	0.48	0.655	5.234	12.000	362.759	3.880E-08
		0.39	0.849	3.936	6.000	276.000	8.580E-04
Number of Spalls	145	0.55	0.674	4.900	12.000	365.405	1.628E-07

Table 34. Influence of Crack Sealing MCPs on the Quality-Performance Correlation (Yes=Significant, No=Not Significant, N/A=Not Applicable)

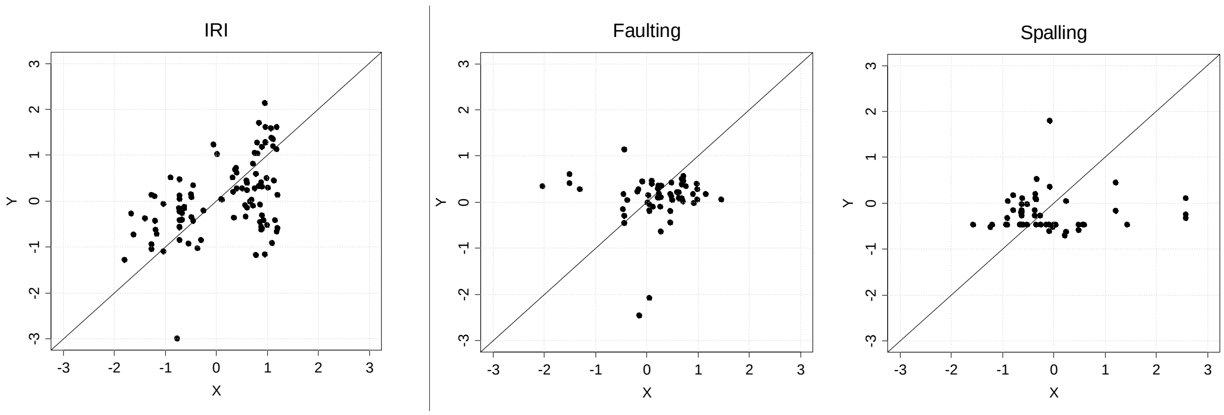
MCPs	IRI	Faulting	Spalling
Shape Factor	No	Yes	No
Silicon sealant	Yes	Yes	Yes
Hot Pour mix sealant	Yes	Yes	Yes
Seal Depth, in.	Yes	Yes	Yes

Table 35 presents the standardized coefficients for the canonical models that relate the MCPs of crack sealing to pavement performance, which were then used for computing canonical variates (X and Y in Figure 7). Figure 7 shows a scatter plot of the canonical variates for crack sealing sections with complete data.

The results of the CCA for crack sealing are similar to those for joint resealing. The correlations between the initial quality of crack sealing (represented by shape factor, sealant type, and seal depth) and in-service performance (faulting, spalling, and IRI) of the treated pavement suggest that crack sealing is suitable for PRS.

Table 35. Coefficients of Crack Sealing Canonical Correlation Models

Variables	IRI Model Coefficients	Faulting Model Coefficients	Spalling Model Coefficients
MCPs (X_i):			
Shape Factor	−0.412	0.105	−0.047
Silicon Sealant	0.621	−0.208	−0.051
Hot Pour Mix Sealant	−0.301	−0.829	0.702
Seal Depth, inch	0.377	0.625	0.734
Performance (Y_i):			
Age 1–3	−1.124	−1.169	−0.490
Age 4–6	2.674	−0.526	1.353
Age 7–9	−0.859	1.040	−0.145



(a) (b) (c)

Figure 7. Scatter plots of crack sealing canonical variates, where Y=linear combination of performance indicator at ages 1–3, 4–6, and 7–9 years and X= linear combination of MCPs affecting performance: (a) IRI; (b) Faulting; (c) Spalling.

3. Diamond Grinding

A total of 37 LTPP diamond grinding sections were used in this analysis. These sections are located in 17 states. Tables 36 and 37 provide descriptive statistics of the construction properties and the performance indicators of these sections, respectively. Of the 37 diamond grinding sections used in the CCA, 36 sections were used in the IRI analysis and 32 sections were used in the faulting and spalling analyses.

Table 36. Descriptive Statistics for Diamond Grinding MCPs

MCPs	Mean	Std. Dev.	Min	Max
Avg. depth of cut, in	0.224	0.109	0.020	0.50
Cutting head width, in	43.65	13.58	30.00	72.00
Initial IRI after Grinding, m/km	1.085	0.404	0.540	2.06

Table 37. Descriptive Statistics for Performance Indicators of Diamond Ground Pavements

Performance Indicator	Age Group	Mean	Std. Dev.	Min	Max
IRI, m/k m	1–3	1.126	0.388	0.59	2.52
	4–6	1.465	0.528	0.84	2.86
	7–9	1.706	0.750	0.68	3.69
Faulting, mm	1–3	0.837	0.732	0.00	2.40
	4–6	1.598	1.113	0.00	3.60
	7–9	1.833	1.378	0.00	4.30
Number of Spalls	1–3	4.811	6.24	0.00	28.50
	4–6	7.969	7.87	0.00	21.67
	7–9	7.875	9.00	0.00	29.50

As shown in Table 38, one significant canonical correlation was found between the MCPs of diamond grinding and IRI, and three canonical correlations were found between these MCPs and faulting. No correlation was found between these MCPs and spalling. Table 39 shows the influence of diamond grinding MCPs on the quality-performance correlations. Yes in this table indicates that the loading coefficient for the MCP and corresponding performance indicator has an absolute value of at least 0.3; and thus the MCP has meaningful influence on the quality-performance correlation.

Table 38. Diamond Grinding Canonical Correlations and Test of Significance

Performance Indicator	No. of Obs	Canonical Correlation	Wilks' L	F	df1	df2	p-value
IRI	36	0.65	0.566	5.111	4.000	62.000	0.0013
Faulting	32	0.79	0.261	5.186	9.000	63.428	2.86E-05
		0.43	0.699	2.651	4.000	54.000	4.29E-02
		0.38	0.855	4.747	1.000	28.000	3.79E-02
No. of Spalls	32	Insignificant	-	-	-	-	-

Table 39. Influence of Diamond Grinding MCPs on the Quality-Performance Correlation (Yes=Significant, No=Not Significant, N/A=Not Applicable)

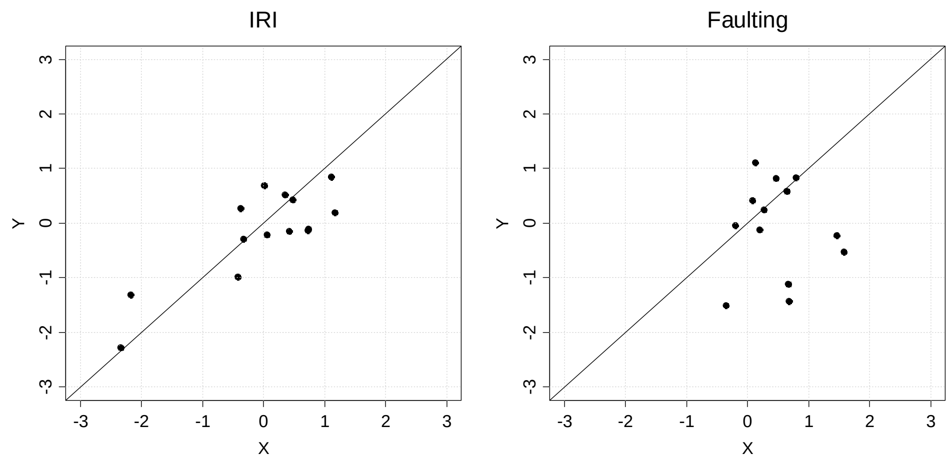
MCPs	IRI	Faulting	Spalling
Avg. depth of cut	Yes	Yes	N/A
Cutting head width	Yes	Yes	N/A
Initial IRI after grinding	Yes	Yes	N/A

Table 40 presents the standardized coefficients for the canonical models that relate the MCPs of diamond grinding to pavement performance, which were then used for computing canonical variates (X and Y in Figure 8). Figure 8 shows a scatter plot of the canonical variates for diamond grinding sections with complete data.

While the CCA results show that there are correlations between initial quality of diamond grinding (represented by cut depth, cutting head width, and initial IRI after grinding) and in-service performance (faulting and IRI), these quality characteristics (and the diamond grinding process in general) are more dependent on the grinding equipment than the contractor's quality control process. Thus, it may be unrealistic to develop PRS for diamond grinding. Nonetheless, diamond grinding was included in the ranking process for identifying treatment types that will be considered in the PRS guide (discussed in a later section of this report).

Table 40. Coefficients of Diamond Grinding Canonical Correlation Models

Variables	IRI Model Coefficients	Faulting Model Coefficients	Spalling Model Coefficients
MCPs (X_i):			
Avg. depth of cut, in	0.43	−0.72	N/A
Cutting head width, in	−0.73	−0.68	N/A
Initial IRI after Grinding, m/km	0.24	−0.59	N/A
Performance (Y_i):			
Age 1–3	−0.76	−0.51	N/A
Age 4–6	3.04	2.03	N/A
Age 7–9	−2.05	−1.47	N/A



(a) (b)

Figure 8. Scatter plots of diamond grinding canonical variates, where Y=linear combination of performance indicator at ages 1–3, 4–6, and 7–9 years and X= linear combination of MCPs affecting performance: (a) IRI; (b) Faulting.

4. Dowel Bar Retrofitting

The LTPP database has 68 dowel bar retrofitting (DBR) sections. However, the data on most of these sections are noisy and incomplete. Table 41 provides descriptive statistics for the performance indicators of 15 of these sections. No detailed data are available on the construction and materials properties of these sections (i.e., dowel bar alignment and properties of patching materials). No meaningful statistical correlation analysis could be performed using these limited data. Thus, the literature was reviewed to determine if the MCPs of DBR are correlated to pavement performance.

While much of the literature on dowel bar alignment focuses on new pavement, the findings of this literature can be extended to retrofitted dowels. Figure 9 illustrates the major types of dowel misalignment (Tayabji 1986).

Table 41. Descriptive Statistics for Performance Indicators of Pavements with DBR

Performance Indicator	Age Group	Mean	Std. Dev.	Min	Max
IRI, m/k m	1–3	1.29	0.90	0.67	3.51
	4–6	1.38	0.87	0.75	3.54
	7–9	1.21	0.23	0.93	1.55
Faulting, mm	1–3	1.25	1.27	0.1	3.4
	4–6	1.71	1.22	0.2	3.1
	7–9	1.8	NA	1.8	1.8
Number of Spalls	1–3	3.38	4.56	0	18.5
	4–6	21.42	11.92	7.67	34.5
	7–9	N/A	N/A	N/A	N/A

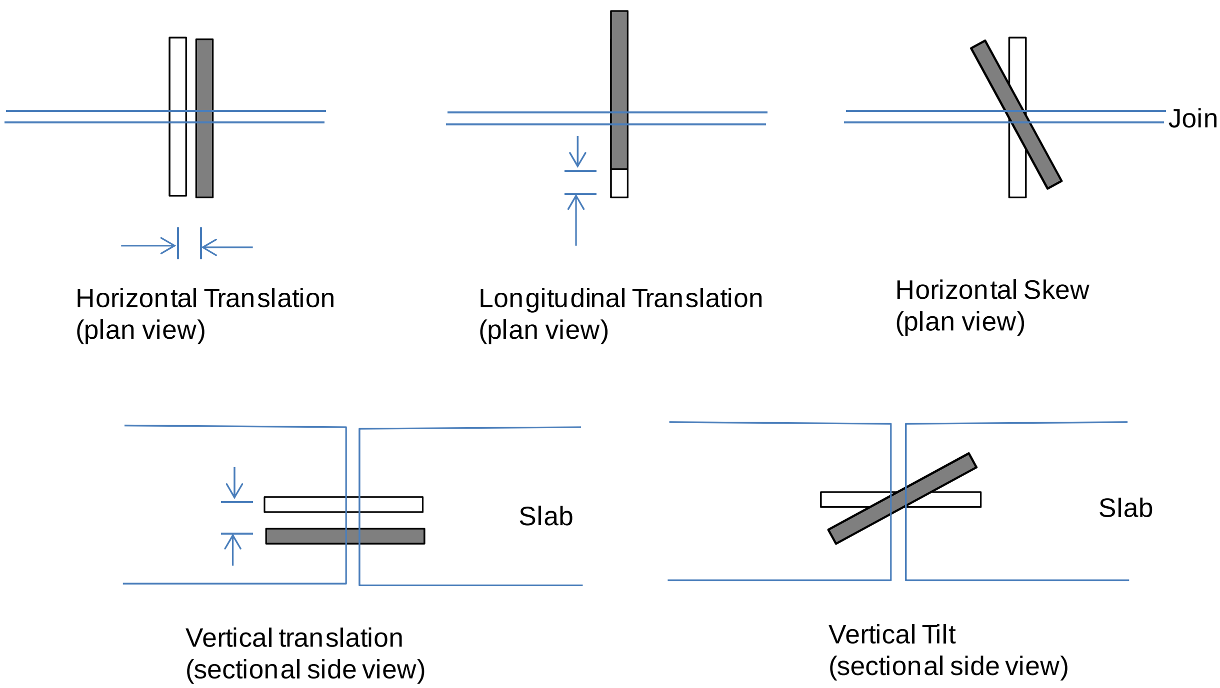


Figure 9. Types of dowel misalignment (Tayabji 1986).

Laboratory testing and finite element analysis conducted as part of a recent NCHRP study found that dowel misalignment can reduce dowel shear capacity and its ability to transfer load across joints (Khazanovich et al. 2009). The same NCHRP study found that major dowel misalignment can increase the potential for faulting, spalling, and IRI. The NCHRP study found that translational and/or rotational misalignments increase the potential for faulting, and reduction in concrete cover due to major vertical translation and/or tilt increases the potential for spalling. Dowel misalignment can potentially increase IRI, as a consequence to increased spalling and faulting. While the NCHRP study focused on dowel bars in new pavement, the findings of that study can be extended to retrofitted dowels. These findings suggest that the following misalignment-related properties of retrofitted dowels can affect pavement performance:

- Patch material cover (vertical translation).
- Embedment length (longitudinal translation).

- Vertical tilt (dowel rotation).
- Horizontal skew (dowel rotation).

Studies have shown that the patch material (i.e., the filler substance used to encase the dowel bar) is a critical factor in the placement of retrofitted load transfer devices (ACPA 2006). The following patch material properties were found to affect pavements performance (Rettner and Snyder 2001, Jerzak 1994, Smith et al. 2008):

- Water content (controlled to reduce the potential for shrinkage cracks and debonding).
- Compressive strength.
- Abrasion loss.
- Final set time.
- Bond to dry and saturated surface dry Portland cement concrete (for patch materials extended with aggregate).
- Flexure strength (for patch materials extended with aggregate).

Additionally, Smith et al. (2008) recommended that DBR patching materials be tested for freeze-thaw durability to ensure long-term performance. Generally, patch materials used for DBR and partial-depth repairs (as discussed next) are similar (FHWA and ACPA 1998) and thus will be treated in a similar manner in this research.

5. Partial-Depth Repair

While the LTPP database has 33 partial-depth repair sections, only 14 of these sections have sufficient data and were used in this analysis. These sections are located in seven states. Tables 42 and 43 provide descriptive statistics of the materials and construction properties and the performance indicators of these sections, respectively.

As shown in Table 44, two significant canonical correlations were found between the MCPs of partial-depth repair and IRI. No CCA was performed for faulting and spalling due to insufficient performance data. Table 45 shows the influence of partial-depth repair MCPs on the correlation between initial quality of partial-depth repair and in-service IRI.

Table 42. Descriptive Statistics for Partial-Depth Repair MCPs

MCPs	Mean	Std. Dev.	Min	Max
Weight of coarse aggregate per unit volume of patch mixture, lb/yd^3	1710.5	354.7	1164	2470
Weight of fine aggregate per unit volume of patch mixture, lb/yd^3	1219.3	174.7	993	1394
Design weight of cement in patch mixture, lb/yd^3	1046.3	711.8	191	2328
Volume of water per unit volume of patch mixture Water, gal/yd^3	31.77	6.14	21	38
Patch 28-day compressive strength, psi	3782.2	698.5	3500	5640
Initial IRI after patching, m/km	1.16	0.44	0.79	2.12

Table 43. Descriptive Statistics for Performance Indicators of Pavements with Partial-Depth Repair

Performance Indicator	Age Group	Mean	Std. Dev.	Min	Max
IRI, m/km	1–3	1.16	0.45	0.79	2.21
	4–6	1.24	0.44	0.88	2.29
	7–9	1.33	0.48	0.94	2.38
Faulting, mm	1–3	1.33	1.54	0.05	4.17
	4–6	1.33	1.87	0	5
	7–9	1.25	2.17	0	4.5
Number of Spalls	1–3	2.67	2.99	0	10
	4–6	4.19	5	0	17
	7–9	1.14	1.21	0	3

Table 44. Partial-Depth Repair Canonical Correlations and Test of Significance

Performance Indicator	No. of Obs	Canonical Correlation	Wilks' L	F	df1	df2	p-value
IRI	14	0.9999	1.21E-05	344.212	10	12	3.65E-13
		0.95	0.105	14.971	4	7	0.0015
Faulting	-	-	-	-	-	-	-
No. of Spalls	-	-	-	-	-	-	-

Table 45. Influence of Partial-Depth Repair MCPs on the Quality-Performance Correlation (Yes=Significant, No=Not Significant, N/A=Not Applicable)

MCPs	IRI	Faulting	Spalling
Coarse aggregate, lb/yd^3	No	N/A	N/A
Fine aggregate, lb/yd^3	Yes	N/A	N/A
Cement, lb/yd^3	Yes	N/A	N/A
Water, gal/yd^3	Yes	N/A	N/A
Patch compressive strength, psi	No	N/A	N/A
Initial IRI after patching, m/km	Yes	N/A	N/A

Table 46 presents the standardized coefficients for the canonical models that relate the MCPs of partial-depth repair to pavement performance, which were then used for computing the canonical variates (X and Y in Figure 10). Figure 10 shows a scatter plot of the canonical variates for partial-depth repair sections with complete data.

While this CCA provides some evidence of correlation between the initial quality of partial-depth repair and IRI, the data are limited to 14 sections only. Thus, the literature was reviewed to verify that the partial-depth repair MCPs and performance are correlated; and thus this treatment type can be considered suitable to PRS.

Table 46. Coefficients of Partial-Depth Repair Canonical Correlation Models

Variables	IRI Model Coefficients	Faulting Model Coefficients	Spalling Model Coefficients
MCPs (X_i):			
Coarse aggregate, lb/yd^3	0.148	N/A	N/A
Fine aggregate, lb/yd^3	0.054	N/A	N/A
Cement, lb/yd^3	0.213	N/A	N/A
Water, gal/yd^3	0.121	N/A	N/A
Patch compressive strength, psi	0.011	N/A	N/A
Initial IRI after patching, m/km	−0.939	N/A	N/A
Performance (Y_i):			
Age 1–3	−0.534	N/A	N/A
Age 4–6	−0.369	N/A	N/A
Age 7–9	−0.104	N/A	N/A

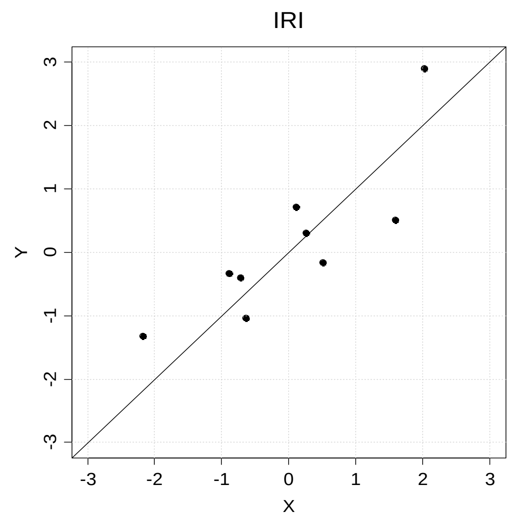


Figure 10. Scatter plots of partial-depth repair canonical variates, where Y=linear combination of IRI at ages 1–3, 4–6, and 7–9 years, and X= linear combination of MCPs affecting IRI.

Past studies (e.g., Mueller et al. 1988, Tang and Zollinger 1997, Markey et al. 2006) suggest that physical properties of patch material that influence the performance of partial-depth repair include:

- Bond strength.
- Shrinkage.
- Modulus of elasticity.
- Compatibility in thermal expansion between the repair material and the original slab.
- Compressive strength.
- Final set time.
- Abrasion.

A wide variety of materials is available for use in partial-depth spall repairs. But high-quality PCC is generally accepted as the most appropriate material for the repair of existing concrete pavements, especially where the depth of repair is greater than 2 in. (WES 1994, Smith et al. 2008).

Construction and placement techniques also influence the performance of partial-depth repairs (Wyant 1984, Wilson et al. 2000). All weak and deteriorated concrete must be located and removed if the repair operation is to be effective. Generally, the area marked for removal should extend 2 to 6 in. outside the defective area in each possible direction (Wilson et al. 2000). The extent of deterioration can be determined by "sounding" the concrete with a solid steel rod, chains, or a ball peen hammer. Smith et al. (2008) recommended minimum repair dimensions of 10-in. long and 4-in. wide.

Based on the results of the above CCA and literature review, one can conclude that partial-depth repair is suitable for PRS.

6. Full-Depth Repair

A total of 34 LTPP full-depth repair sections were used in this analysis. These sections are located in 16 states. Tables 47 and 48 provide descriptive statistics of the materials and construction properties and the performance indicators of these sections, respectively. Of the 34 full-depth repair sections used in the CCA, 26 sections were used in the IRI analysis and 14 sections were used in the faulting analysis. The spalling data were insufficient to conduct CCA for spalling.

Table 47. Descriptive Statistics for Full-Depth Repair MCPs

MCPs	Mean	Std. Dev.	Min	Max
Weight of coarse aggregate per unit volume of patch mixture , lb/yd^3	1798.2	265.4	840	2565
Weight of fine aggregate per unit volume of patch mixture, lb/yd^3	1243.3	382.4	993	2997
Design weight of cement in patch mixture, lb/yd^3	697.8	104.7	500	876
Volume of water per unit volume of patch mixture, gal/yd^3	41.92	39.28	27	225
Mean air content, %	5.47	0.89	4.2	7.8
Mean slump, in.	2.95	1.18	1	6
28-day compressive strength, psi	4645.6	1885.1	341	6710
Initial IRI after patching, m/km	1.15	0.43	0.71	2.64

As shown in Table 49, one significant canonical correlation was found between the MCPs of full-depth repair and IRI, and one significant canonical correlation was found between these MCPs and faulting. Table 50 shows the influence of full-depth repair MCPs on the quality-performance correlations. Yes in this table indicates that the MCP has meaningful influence on the quality-performance correlation. Air content and 28-day strength were not included in the CCA for faulting data because many of the sections do not have data on these properties.

Table 48. Descriptive Statistics for Performance Indicators of Pavements with Full-Depth Repair

Performance Indicator	Age Group	Mean	Std. Dev.	Min	Max
IRI, m/k m	1–3	1.29	0.78	0.71	4.45
	4–6	1.41	0.73	0.75	4.32
	7–9	1.57	0.76	0.94	4.67
Faulting, mm	1–3	1.2	1.68	0	5.7
	4–6	1.41	1.38	0	4.7
	7–9	1.48	1.09	0.25	3.1
Number of Spalls	1–3	5.15	5.21	0	19
	4–6	14.92	11.56	0	35
	7–9	8	10.17	0	22

Table 49. Full-Depth Repair Canonical Correlations and Test of Significance

Performance Indicator	No. of Obs	Canonical Correlation	Wilks' L	F	df1	df2	p-value
IRI, m/k m	26	0.91	0.127	1.908	24	44	0.0310
Faulting, mm	14	0.99	0.010	3.388	18	15	0.0112
Spalling Number	12	-	-	-	-	-	-

Table 50. Influence of Full-Depth Repair MCPs on the Quality-Performance Correlation (Yes=Significant, No=Not Significant, N/A=Not Applicable)

MCPs	IRI	Faulting	Spalling
Coarse aggregate, lb/yd^3	No	No	N/A
Fine aggregate, lb/yd^3	No	No	N/A
Cement, lb/yd^3	No	No	N/A
Water, gal/yd^3	Yes	No	N/A
Mean air content, %	No	-	N/A
Mean slump, in.	No	No	N/A
28-day compressive strength, psi	Yes	-	N/A
Initial IRI after patching, m/km	Yes	Yes	N/A

Table 51 presents the standardized coefficients for the canonical models that relate the MCPs of full-depth repair to pavement performance, which were then used for computing canonical variates (X and Y in Figure 11). Figure 11 shows a scatter plot of the canonical variates for full-depth repair sections with complete data.

Table 51. Coefficients of Full-Depth Repair Canonical Correlation Models

Variables	IRI Model Coefficients	Faulting Model Coefficients	Spalling Model Coefficients
MCPs (X_i):			
Coarse aggregate, lb/yd^3	0.096	4.295	N/A
Fine aggregate, lb/yd^3	0.008	−6.256	N/A
Cement, lb/yd^3	0.162	2.929	N/A
Water, gal/yd^3	0.28	0.153	N/A
Mean air content, %	−0.129	-	N/A
Mean slump, in.	0.149	1.604	N/A
28-day compressive strength, psi	−0.665	-	N/A
Initial IRI, m/km	−0.686	0.259	N/A
Performance (Y_i):			
Age 1–3	2.227	1.188	N/A
Age 4–6	−7.611	0.847	N/A
Age 7–9	4.731	−1.508	N/A

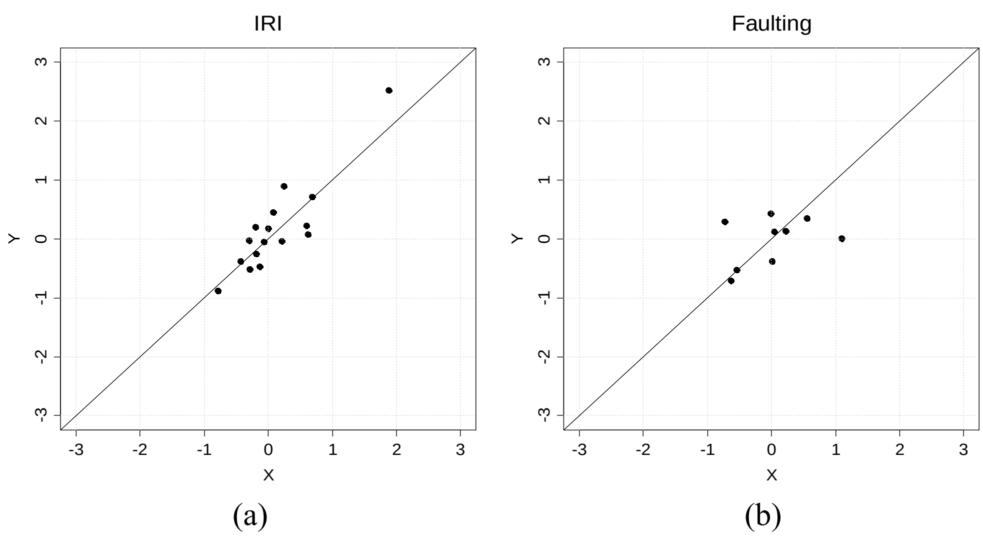


Figure 11. Scatter plots of full-depth repair canonical variates, where Y=linear combination of performance indicator at ages 1-3, 4-6, & 7-9 years and X= linear combination of MCPs affecting performance: (a) IRI; (b) Faulting.

While the correlations between initial quality of full-depth repair and in-service performance (faulting and IRI) suggest that this treatment is suitable for PRS, the utilization of full-depth repair as a preservation treatment is questionable. For the purpose of this research, preservation treatments are defined as treatments applied to preserve an existing roadway, slow future deterioration, and maintain and improve its functional condition (without substantially increasing structural capacity). In many instances, full-depth repair has been used to address structural problems (e.g., problems in the base). This fact has lowered the ranking of this treatment for consideration in the PRS guide (see discussion of treatments rankings in the next section of this report).

7. Undersealing

A total of 15 LTPP undersealing sections were found. However, no analysis could be performed on these sections due to missing and noisy data. Additionally, the literature has limited information on undersealing, compared to other treatment types. However, it is generally accepted that indicators of undersealing quality include (Smith et al. 2008):

- Reduction in slab deflection (difference between before and after grout injection).
- Accurately locating the areas of voids beneath the slab.

While the LTPP data and the literature do not provide sufficient evidence that undersealing is suitable for PRS; no contrary evidence could be found either. Thus, this treatment was rated for consideration in the PRS guide; however, it received low ranking due to the above issues.

Ranking of Treatments for Consideration in PRS Guide

Since more than six treatments were found to be suitable for PRS, they were ranked and prioritized to select a maximum of six treatments for consideration in the PRS guide (to developed in Task 6 of this project). Treatments are evaluated and rated based on the following items:

1. Quality of available data.
2. Quantity of available data.
3. Availability of materials and construction properties that (1) correlate with in-service performance, (2) can be measured at the time of construction; and (3) can be controlled by the contractor/material supplier.
4. Feasibility of developing performance prediction models that (1) link initial quality to in-service performance, and (2) consider the effect of existing pavement condition on treatment performance.
5. Extent of usage as a preservation treatment.

A combination of direct rating and the Analytic Hierarchy Process (AHP) was used to rate and rank the 12 treatments found suitable for PRS. This approach is relatively simple and at the same time ensures consistent rankings. The AHP was used to develop weights for the five items that comprise the evaluation criteria. A direct 1–9 rating was then assigned for each treatment based on each individual item of the evaluation criteria. Table 52 shows the 1–9 scale that was used in the rating process.

Table 52. Rating Scale and Definitions

Scale(1)	Evaluation Criteria Pairwise Comparisons (Saaty 1990)	Treatment Comparisons
1	Equal importance	Slightly Favored
3	Moderate importance of one over another	Moderately Favored
5	Essential or strong importance	Strongly Favored
7	Very strong importance	Very Strongly Favored
9	Extreme importance	Extremely Favored

(1) The values 2, 4, 6, and 8represent intermediate rates.

Weights for the five items of the evaluation criteria were determined by comparing these items in a pairwise fashion to determine how much more or less important one item is compared to the other. The pairwise comparisons are stored in a *5x5* matrix (see Figure 12). These pairwise comparisons represent the consensus of five members of the research team. These team members are Nasir Gharaibeh (Principle Investigator), Dan Zollinger (group leader for PCC-surfaced pavement), Tom Freeman (group leader for HMA-surfaced pavement), Jon Epps (researcher), and Arif Chowdhury (researcher).

Weights for the five evaluation items are determined by calculating the principal eigenvector associated with the maximum eigenvalue for the matrix shown in Figure 12. This principal eigenvector is normalized to create a relative ratio scale that can be used as weights for the items of the evaluation criteria. The maximum eigenvector and its normalized counterpart that represents the weights of the five items of the evaluation criteria are shown in Table 53. The calculations of eigenvalues and eigenvectors are not discussed here for brevity; but they can be found in most algebra textbooks.

Evaluation Criteria	Quality of Available Data	Quantity of Available Data	Existance of quality charactreistics that can be measured at the time of construction and can be controlled by the contractor/material supplier	Feasibility of developing performance prediction models that link initial quality to in-service performance	Treatment Usage
Quality of Available Data	1	2/1	2/1	3/1	4/1
Quantity of Available Data		1	2/1	1/2	3/1
Existance of quality charactreistics that can be measured at the time of construction and can be controlled by the contractor/material supplier			1	2/1	4/1
Feasibility of developing performance prediction models that link initial quality to in-service performance				1	2/1
Treatment Usage					1

Figure 12. Pairwise comparison matrix representing the consensus of the researchers.

Table 53. Weights of the Five Items of the Evaluation Criteria

Evaluation Criteria Item	**Maximum Eigenvector**	**Weight**
W_1: Quality of available data	0.729	0.361
W_2: Quantity of available data	0.402	0.198
W_3: Availability of appropriate materials and construction properties[(1)]	0.410	0.203
W_4: Feasibility of developing required performance prediction models[(2)]	0.347	0.171
W_5: Extent of usage as a preservation treatment	0.135	0.067

(1) Materials and construction properties that correlate with in-service performance, can be measured at the time of construction; and can be controlled by the contractor/material supplier.

(2) Models that link initial quality to in-service performance, and consider the effect of existing pavement condition on treatment performance.

The five team members then assigned a direct 1-9 rating for each treatment based on each individual evaluation criterion. The overall rating of each treatment is computed as:

$$OR_t = \sum_{i=1}^{5} w_i \times R_{ti}$$

where OR_t = Overall 1-9 rating of treatment *t*.
w_i = weight of evaluation criteria item *i (i=1, …,5).*
R_{ti} = Direct rating of treatment *t* based on evaluation criteria item *i*.

Tables 54 and 55 show the individual and overall ratings and rankings for HMA and PCC treatment types, respectively. Based on these rankings, the researchers recommend the following treatments to be considered in the PRS guide:

- HMA-surfaced Pavement: Chip seals, thin HMA overlays, and slurry seals.
- PCC-surfaced Pavement: Dowel bar retrofitting, joint resealing, and partial-depth repair.

Table 54. Ratings and Ranking of HMA Treatments

Evaluation Item / Treatment	W_1 = 0.361	W_2 = 0.198	W_3 = 0.203	W_4 = 0.171	W_5 = 0.067	Overall Rating (1–9 scale)	Rank
Chip Seals	9	9	9	8	7	8.7	1*
Crack Sealing	2	4	2	1	9	2.7	5
Slurry Seals	7	5	7	7	5	6.5	3*
Hot-in-Place Recycling	8	4	7	7	2	6.4	4
Thin HMA Overlay	8	7	9	9	8	8.2	2*

(*) Treatment recommended for consideration in PRS Guide

Table 55. Ratings and Ranking of PCC Treatments

Evaluation Item / Treatment	W_1 = 0.361	W_2 = 0.198	W_3 = 0.203	W_4 = 0.171	W_5 = 0.067	Overall Rating (1–9 scale)	Rank
Partial-Depth Repair	7	6	6	4	6	6.0	3*
Undersealing	4	2	3	5	6	3.7	7
Dowel Bar Retrofitting	6	5	9	9	5	6.9	1*
Diamond Grinding	3	6	8	2	7	4.7	6
Full-Depth Repair	5	6	7	4	2	5.2	5
Crack Sealing	6	7	4	6	8	5.9	4
Joint Resealing	6	7	5	7	8	6.3	2*

(*) Treatment recommended for consideration in PRS Guide

Subtask 5.2 – Identify Existing Laboratory and Field Tests for the Selected Treatments

As mentioned earlier, acceptance quality characteristics (AQCs) should satisfy the following conditions to be suitable for PRS:

- Can be measured at the time of construction.
- Can be controlled by the contractor or material supplier.
- Affect the future performance of the preservation treatments.

Materials and construction properties that meet the above criteria have been identified for the six recommended pavement preservation treatments. These properties have been identified based on the statistical analysis conducted under Subtask 5.1, review of the literature, and review of a sample of state specifications (conducted in Phase I of the project). Tables 56–58 list these materials and construction properties for thin HMA overlays, chip seals, and slurry seals. Tables 59–61 list these materials and construction properties for dowel bar retrofitting, joint resealing, and partial-depth repair. The final AQCs will be determined as part of the performance modeling process. Properties that can be incorporated as inputs to the performance prediction models will be included in the PRS as key AQCs for these preservation treatments.

Table 56. Potential AQCs for Thin HMA Overlay

Materials and Construction Property (MCP)	Found to correlate with at least one performance indicator based on Subtask 5.1 analysis of LTPP data	Literature suggesting MCP is feasible to measure and affects performance(1)	Example state DOTs specifying MCP in current specifications
Overlay thickness, in.	Yes	Yes	KS, MI
Percent passing #4 Sieve	Yes	Yes	TX, FL, MI, KS
Percent passing #200 Sieve	Yes	Yes	TX, FL, MI, KS
Percent asphalt content	Yes	Yes	MI, TX, FL
Percent air voids	Yes	Yes	MI, TX, KS, FL
Initial Smoothness	NA(2)	Yes	TX, KS, FL
Overlay thickness to nominal maximum aggregate size (NMAS) ratio	NA	Yes	N/A

(1) Example publications: Brown et al. (2004) and Newcomb (2009).
(2) N/A refers to either not applicable or information not available.

Table 57. Potential AQCs for Chip Seal

Materials and Construction Property (MCP)	Found to correlate with at least one performance indicator based on Subtask 5.1 analysis of LTPP data	Literature suggesting MCP is feasible to measure and affects performance(1)	Example state DOTs specifying MCP in current specifications
Asphalt application rate ratio	Yes	Yes	MI, AZ, CA, MT, IA, NC, NY, WA, TX, ID
Aggregate application rate ratio	Yes	Yes	MI, CA, MT, IA, NC, NY, WA, TX, ID
Flakiness index	Yes	Yes	MI, AZ, NY, SD, TX
Percent passing #4 sieve	Yes	Yes	MI, AZ, CA, MT, IA, NC, NY, WA, TX, ID
Percent passing #200 sieve	Yes	Yes	MI, AZ, CA, MT, IA, NC, NY, WA, TX, ID
Penetration, 0.1 mm	Yes	NA(2)	MI, CA, MT,
Viscosity at 50°C, s	Yes	NA	MI, AZ, CA, MT, IA, NC, NY, SD, WA, TX, ID

(1) Example publications: Gransberg and James 2005, Smith et al. 1993; Bullard et al. 1992.
(2) N/A refers to either not applicable or information not available.

Table 58. Potential AQCs for Slurry Seal

Materials and Construction Property (MCP)	Found to correlate with at least one performance indicator based on Subtask 5.1 analysis of LTPP data	Literature suggesting MCP is feasible to measure and affects performance(1)	Example state DOTs specifying MCP in current specifications
Penetration, 0.1 mm	Yes	Yes	CA, AZ,MI
Viscosity at 25°C, s	Yes	Yes	CA, AZ, IA, MI
Percent passing #4 sieve	Yes	Yes	CA, AZ, IA, PA
Percent passing #200 sieve	Yes	Yes	CA, AZ, IA, PA
Aggregate moisture	Yes	NA(2)	N/A
Residual Asphalt Content	N/A	Yes	CA, AZ, MI, PA
Slurry application rate ratio	Yes	Yes	CA, AZ

(1) Example publications: ISSA 2010, Gransberg 2010.
(2) N/A refers to either not applicable or information not available.

Table 59. Potential AQCs for Joint Resealing

Materials and Construction Property (MCP)	Found to correlate with at least one performance indicator based on Subtask 5.1 analysis of LTPP data	Literature suggesting MCP is feasible to measure and affects performance(1)	Example state DOTs specifying MCP in current specifications
Shape factor	Yes	Yes	NY, AZ, IA, MI
Use of bond breaker between the sealant and the bottom of the reservoir (backer rod or tape)	Yes	N/A	TX, SD, NY, MI, AZ, CA
Refacing of sidewalls	Yes	Yes	TX, NY, PA, AZ, CA
Sealant type	Yes	Yes	WA, NY, SD, IA, MI, CA, FL, TX, AZ
Seal depth	Yes	Yes	WA, AZ, IA, MI, NY
Bond strength	N/A	Yes	WA, SD, PA, CA
Resilience (Hot Poured Sealant)	N/A	N/A	SD, PA, CA
Tensile stress (Silicone Joint Sealant)	N/A	N/A	SD, PA, CA
Elongation (Silicone Joint Sealant)	N/A	Yes	SD, PA, CA
Durometer hardness (Silicone Joint Sealant)	N/A	N/A	SD, PA, CA

(1) Example publications: Gurjar et al. 1996, 1998; Weisgerber 1992.
(2) N/A refers to either not applicable or information not available.

Table 60. Potential AQCs for Dowel Bar Retrofitting

Materials and Construction Property (MCP)	Found to correlate with at least one performance indicator based on Subtask 5.1 analysis of LTPP data	Literature suggesting MCP is feasible to measure and affects performance(1)	Example state DOTs specifying MCP in current specifications
Dowel alignment	N/A(2)	Yes	AZ, PA, SD, TX, WA, NY, CA
Compressive strength of patch material	N/A	Yes	PA, SD, TX, CA
Flexural strength of patch material	N/A	Yes	PA, CA
Bond Strength	N/A	Yes	PA, WA, CA
Drying Shrinkage	N/A	Yes	CA, NY, WA
Abrasion loss	N/A	Yes	CA
Final set time	N/A	Yes	SD

(1) Example publications: Khazanovich et al. 2009, Rettner and Snyder 2001, Jerzak 1994, Smith et al. 2008.
(2) N/A refers to either not applicable or information not available.

Table 61. Potential AQCs for Partial-Depth Repair

Materials and Construction Property (MCP)	Found to correlate with at least one performance indicator based on Subtask 5.1 analysis of LTPP data	Literature suggesting MCP is feasible to measure and affects performance[1]	Example state DOTs specifying MCP in current specifications
Compressive strength of patch material	Yes	Yes	TX, WA, IA, PA, NY, AZ, CA
Water content	Yes	Yes	N/A
Cement content	Yes	Yes	MI
Air Content	N/A	No	IA, SD, NY
Bond Strength	N/A	Yes	WA
Drying Shrinkage	N/A	Yes	TX, WA, CA
Final set time	N/A	Yes	IA
Compatibility in thermal expansion between the repair material and the original slab	N/A	Yes	N/A
Abrasion loss	N/A	Yes	CA
Cut depth	N/A	Yes	TX, WA, IA, SD, PA, NY, AZ, CA
Initial Smoothness	Yes	N/A	SD, PA

(1) Example publications: Mueller et al. 1988, Tang and Zollinger 1997, Markey et al. 2006.

(2) N/A refers to either not applicable or information not available.

Subtask 5.3 – Identify Data Sources for the Selected Treatments

For the recommended HMA treatments (i.e., thin HMA overlays, chip seal, and slurry seal), the LTPP database was found to contain sufficient data for developing mechanistic-empirical performance prediction models for these treatments. These data were described earlier as part of Subtask 5.1 section of this report.

For PCC treatments (joint resealing, dowel bar retrofitting, and partial-depth repair), the LTPP data were found to be insufficient, and thus will be supplemented with data obtained from laboratory testing. A discussion of these supplementary data is provided in the next sections.

Joint Resealing

In addition to the MCPs available in the LTPP database (shape factor, refacing, sealant type, sealant depth, and bottom bond breaker), two additional MCPs have been found in past studies to affect the performance of joint seals in terms of debonding: moisture condition and cleanliness of the concrete joint walls at the time of installation of the joint seal. Past studies have found moisture content of the concrete surface (i.e., moisture held in the capillary pores of the concrete) to adversely affect the capability of the concrete to adhere to a sealant material and that this property can now be detected by dielectric measures (Lee and Zollinger 2011, Lee et al. 2009). Existing data on bond strength for 78 different joint seal combinations including sealant type, coarse aggregate type, surface preparation, cure temperature, and cure humidity are available for use in this project. These data were generated from a previous extensive laboratory testing program and are described in Gurjar (1996), Gurjar et al. (1996), and Gurjar et al. (1998). Limited laboratory work will be conducted as part of Subtask 6.1 to extend the moisture data in the Gurjar study in terms of measuring dielectric values; which will make bond strength (an input to the joint resealing performance prediction model) applicable to field testing and the PRS process.

Part of the laboratory testing will be dedicated to incorporating a component in the bonding model for cleanliness. To date, the cleanliness of joint sidewalls has been difficult to quantify under field conditions. However, black light (long wave ultra violet light) provides an opportunity for detecting free dust on joint sidewalls. Such a test requires a dark room and black light source for direct visual inspection. This method has been a pass/fail test that can work on any material with a contaminant that fluoresces under black light. The inspector simply places a wiping cloth under the black light and inspects the cloth to assess the amount of contamination as low, medium, or high. While this method has limitations, it is promising especially where the contaminants fluoresce and are noticeable enough for quantification purposes.

Dowel Bar Retrofitting

For dowel bar retrofitting, the detailed Falling Weight Deflectometer (FWD) data files in the LTPP database contain data that can potentially be used to compute relevant parameters for both before and after retrofitting the dowel bars. The parameters include:

- Load transfer efficiency
- Effective slab thickness
- Modulus of dowel support
- Dowel bar looseness

Load transfer efficiency (LTE), measured from FWD data, can be used to determine improvement due to dowel bar retrofitting by considering before and after treatment LTEs. Effective slab thickness, determined from the FWD deflection profile, represents the structural integrity of the pavement section in terms of the overall slab thickness. The modulus of dowel support represents the stiffness of the grout immediately below the dowel. Dowel bar looseness indicates the presence of voids in and around the dowel bar. Again, these parameters can be obtained from the FWD test files stored in the LTPP database and are expected to be useful MCPs for dowel bar retrofitting.

Additionally, effective dowel bar diameter can potentially be used as an additional MCP. As discussed earlier, this parameter was developed under NCHRP Project 10-69 to account for the effect of misalignment in dowel bars on pavement performance.

Partial Depth Repair

Partial depth repair fails primarily due to delamination of the repair concrete (and eventual spalling) from the substrate layer. Delamination occurs often due to excess shrinkage strains in the repair material resulting from high cement contents and improper curing. Although the available data in the LTPP database is limited, the information on mixture design should be useful to determine set temperature and the amount of drying shrinkage permissible for a given set of curing conditions. However, some effort will need to be made to ascertain the weather conditions at the time of installation for these LTPP sections. From this information an assessment of the potential for delamination can be made, and then in-service performance can projected. Much of the MCP data listed in Table 61 will be useful in this approach but it is anticipated that limited additional laboratory testing may be necessary to relate curing quality and weather conditions to distresses noted in the database.

As discussed earlier, patch materials used for partial-depth repair and dowel bar retrofitting are similar (FHWA and ACPA 1998) and thus will be treated in a similar manner in this research.

Closure

The suitability of 12 pavement preservation treatment types for PRS was assessed based on a statistical analysis of LTPP data and a comprehensive review of the literature. These treatment types were then ranked based on 5-item evaluation criteria using a structured rating and ranking process. The six treatments that have been selected for consideration in the PRS guide are:

- HMA-surfaced Pavement: Thin HMA overlays, chip seals, and slurry seals.
- PCC-surfaced Pavement: Dowel bar retrofitting, joint resealing, and partial-depth repair.

The LTPP database was found to contain sufficient data for the selected HMA treatment types. However, for the selected PCC treatment types, the LTPP data will need to be supplemented with additional laboratory testing data (to be generated in Task 6 of this project).

Under Task 6 of the project, the compiled data will be used for developing performance prediction models for the selected treatment types. Through these models, the treatment’s material and construction quality is related to its in-service performance. The total life-cycle costs of the as-designed and as-constructed treatments are then computed based on the predicted performance.

REFERENCES

American Concrete Pavement Association (ACPA) (2006). *Concrete Pavement Field Reference-Preservation and Repair*. Engineering Bulletin EB239P. American Concrete Pavement Association, Skokie, IL.

Brown, E. R., M. R., Hainin, Cooley, A., and Hurley, G. (2004). *Relationship of Air Voids, Lift Thickness, and Permeability in Hot Mix Asphalt Pavements*. NCHRP Report 531, National Cooperative Highway Research Program (NCHRP), Transportation Research Board, Washington, D.C.

Bullard, D. J., Smith, R. E., and Freeman, T. J. (1992). *PDevelopment of a Procedure to Rate the Application of Pavement Maintenance Treatments*. Report No. SHRP-M/FR-92-102, Strategic Highway Research Program, National Research Council, Washington, D.C.

Federal Highway Administration (FHWA) and American Concrete Pavement Association (ACPA). (1998). *Concrete Pavement Rehabilitation: Guide for Load Transfer Restoration*. FHWA-SA-97-103, ACPA Bulletin JP001P. Federal Highway Administration, Washington, D.C., and American Concrete Pavement Association, Skokie, IL.

Gebers, M.A., and R.C., Peck, 2003. "Using Traffic Conviction Correlates to Identify Highway Accident-Risk Drivers," *Accident Analysis & Prevention*, 35, 2003, pp. 903–912.

Gransberg, D. D. (2010). *Microsurfacing*. NCHRP Synthesis of Highway Practice 411, Transportation Research Board, Washington, D.C.

Gransberg, D. D. and James, D. M. B. (2005). *Chip Seal Best Practices*. NCHRP Synthesis of Highway Practice 342, Transportation Research Board, Washington, D.C.

Gurjar, A., D. G. Zollinger, and Tang, T. (1996). "Strain and Age Effects on Behavior of a Concrete Pavement Joint Sealant Material." *Transportation Research Record: Journal of the Transportation Research Board*, No. 1529, Transportation Research Board of the National Academies, Washington, D.C., pp. 95–100.

Gurjar, A. H. (1996). "Characterization of Viscoelastic Joint Sealants in Concrete Pavements." PhD Thesis, Texas A&M University, College Station, TX, December 1996.

Gurjar, A., Kim, H. B., Moody, E., and Buch, N. J. (1998). "Laboratory Investigation of Factors Affecting Bond Strength in Joint Sealants." *Transportation Research Record: Journal of the Transportation Research Board*, No. 1627, Transportation Research Board of the National Academies, Washington, D.C., pp. 13–21.

International Slurry Surfacing Association (ISSA). (2010). Inspector's Manual for Slurry Systems, ISSA, Annapolis, MD.

Jerzak, H. (1994). *Rapid Set Materials for Repairs to Portland Cement Concrete Pavement and Structures*. California Department of Transportation, Sacramento, CA.

Khazanovich, L., Hoegh, K., and Snyder, M. (2009). *Guidelines for Dowel Alignment in Concrete Pavements*. NCHRP Report No. 637, Transportation Research Board, Washington, D.C.

Lee, S. I., Zollinger, D. G. (2011). "Estimating Volume Fraction of Free Water in Fresh Concrete by Interpretation of Dielectric Constant." ASCE Ms. No. MTENG-690, Journal of Materials in Civil Engineering, Paper accepted for publication July, 2011.

Lee, S. I., Zollinger, D. G., Lytton, R. L., and Jackson, N. (2009). "Automation of Pavement Sublayer Moisture Content Determination Using LTPP Time Domain Reflectometry Data and Micromechanics." *Transportation Research Record: Journal of the Transportation Research Board*, No. 2016, pp. 16-26.

Levine, M.S. *Canonical Analysis and Factor Comparison.* Sage Publications, Inc., California, 1977.

Markey, S. M., Lee, S.I., Mukhopadhyay, A. K., Zollinger, D. G., Whitney, D. P., and Fowler, D. W. (2006). *Investigation of Spall Repair Materials for Concrete Pavement*. Report No. FHWA/TX-06/0-5110-1, Federal Highway Administration and Texas Department of Transportation.

Morian, D. A. (2011). *Cost Benefit Analysis of Including Microsurfacing in Pavement Treatment Strategies & Cycle Maintenance.* Federal Highway Administration and Pennsylvania Department of Transportation, Publication No. FHWA-PA-2011-001-080503.

Mueller, P., Zaniewski, J., and Tritsch, S. (1988). "Concrete Pavement Spall Repair." Preprint Paper Presented at the Sixty-Seventh Annual Meeting of the Transportation Research Board. Transportation Research Board, Washington, D.C.

Newcomb, D. E. (2009). *Thin Asphalt Overlays for Pavement Preservation*. Information Series 135, National Asphalt Pavement Association (NAPA), Lanham, MD.

Rettner, D. L. and Snyder, M. B. (2001). "An Evaluation of Retrofit Load Transfer Materials and Dowel Bar Configurations." *Proceedings, 7th International Conference on Concrete Pavements*, Orlando, FL, pp. 669–684.

Saaty, T. L. (1990). "Multicriteria Decision Making: the Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation." RWS publications, Pittsburgh, PA.

Smith, K. D., Hoerner, T. E., and Peshkin, D. G. (2008). *Concrete Pavement Preservation Workshop- Reference Manual*. Federal Highway Administration, Iowa State University.

Pavement Maintenance Effectiveness

Smith, R., T. Freeman, T., and Pendleton, O. (1993). *Pavement Maintenance Effectiveness*. Report No. SHRP-H-358, Strategic Highway Research Program, National Research Council, Washington, D.C.

Smith, R.E. and Beatty, C.K. (1999). "Microsurfacing Usage Guidelines." *Transportation Research Record: Journal of the Transportation Research Board*, No. 1680, Transportation Research Board of the National Academies, Washington, D.C., pp. 13–18.

Smith, K. L. and Peshkin, D. G. (2011). "Pavement Preservation on High Traffic Volume Roadways." Presented at the 90th Transportation Research Board Meeting, Washington, D.C.

Tang, T. and Zollinger, D.G. (1997). *Investigation of Spall Repair for Concrete Pavements*. Research Report TX-98/2919-3, TTI 2919-3, Texas Transportation Institute, The Texas A&M University System, Texas Department of Transportation.

Tayabji, S.D. (1986). "Dowel Placement Tolerances for Concrete Pavements." *Transportation Research Record*, No. 1062, TRB, National Research Council, Washington, D.C., pp. 47–54.

Transportation Research Board (TRB) (2009). "Glossary of Highway Quality Assurance Terms," Transportation Research Board, Electronic Circular E-C137, 4th Update, Washington, D.C.

Waterways Experiment Station (WES). (1994). *Spall Repair*. REMR Technical Note CS-MR-4.5. Supply 6, Army Engineer Waterways Experiment Station, Vicksburg, MS.

Weisgerber, F. E. and C. P. Wang (1992). "Stress Distributions in Highway Joint Seals." Science and technology of building seals, sealants, glazing, and waterproofing, Second Volume.

Wilson, T. P., Smith, K. L., and Romine, A. R. (2000). *Materials and Procedures for Rapid Repair of Partial-Depth Spalls in Concrete Pavement, Manual of Practice.* Report No. FHWA-RD-99-152. Federal Highway Administration, McLean, VA.

Wyant, D. (1984). *Evaluation of Concrete Patching Materials*. Virginia Highway and Transportation Research Council, Charlottesville, VA.