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Improving the Use of Crack Sealing to Asphalt Pavement in Louisiana

by

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16. Abstract

The use of crack sealing in Louisiana has been limited as studies conducted in the 1960s showed that the performance of this maintenance practice can be affected by shallow groundwater table conditions in the state. The objective of this study was twofold. First, this project quantified the short-term and long-term benefits of using crack sealing, chip seal, and microsurfacing. Furthermore, this project assessed the optimal application timing of crack sealing, chip seal, and microsurfacing. Second, this project evaluated potential moisture damage in pavements treated with crack sealing, chip seal, and microsurfacing. Results showed that crack sealing could be applied in Louisiana for any groundwater table depth without the potential for moisture damage given proper design and construction. On the other hand, microsurfacing should be avoided in areas with shallow groundwater table as it could contribute to moisture damage in asphalt pavements due to moisture entrapment. To facilitate implementation of the results, a user-friendly tool was developed in the form of a spreadsheet that could be used by the Department during planning and design of maintenance activities.

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ABSTRACT

One of the most critical distresses in asphalt concrete (AC) pavement is surface cracking, which allows water infiltration through the cracks, causing stripping in asphalt pavement layers, and weakening and deteriorating the base and/or subgrade. Crack sealing and filling are used by many states on a routine basis for preventive maintenance. Crack sealing and filling prevent the egress of water in the pavement structure, thus avoiding the weakening of the pavement and delaying its deterioration. The use of crack sealing in Louisiana has been limited as studies conducted in the 1960s showed that the performance of this maintenance practice can be affected by the shallow groundwater table conditions in the state. According to these studies, crack sealing can prevent water from escaping through the cracks and therefore, cause an acceleration of asphalt stripping in the overlay. Yet, the use of any impermeable treatment including overlays on top of a pavement with shallow groundwater table may cause the same problem.

The objective of this study was twofold. First, this project quantified the benefits of using crack sealing, chip seal, and microsurfacing with respect to their ability to provide immediate and long-term benefits. Furthermore, this project assessed the optimal application timing of crack sealing, chip seal, and microsurfacing by evaluating the cost effectiveness of these treatments using common economic measures. Based on this evaluation, the research team developed regression models that predict crack sealing benefits in terms of extension in pavement service life, based on the project conditions. Second, this project evaluated potential moisture damage in AC treated with crack sealing, chip seal, and microsurfacing. Based on this evaluation, the research team developed a regression model that determines whether crack sealing should be used to avoid moisture damage in a cracked pavement based on the ground water table depth and air relative-humidity.

Results showed that crack sealing could be applied in Louisiana for any groundwater table depth without the potential for moisture damage given proper design and construction. On the other hand, microsurfacing should be avoided in areas with shallow groundwater table as it could contribute to moisture damage in asphalt pavements due to moisture entrapment. To facilitate implementation of the results, a user-friendly tool was developed in the form of a spreadsheet that could be used by the Department during the planning and design of maintenance activities. This tool requires the user to input key project conditions such as the average daily traffic volume, thickness of the existing asphalt pavement, and pre-treatment pavement conditions. Based on the provided input values, the tool would then select the most cost-effective maintenance treatment (crack sealing, chip seal, microsurfacing or do nothing) that addresses existing surface distresses without causing moisture damage.

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IMPLEMENTATION STATEMENT

Based on the findings of this project, it is recommended to use crack sealing in routine preventive maintenance activities according to the guidelines developed in this study. On the other hand, microsurfacing should be avoided in Southern Louisiana in areas with a shallow groundwater table as it could contribute to moisture damage in asphalt pavements due to moisture entrapment. Using the developed spreadsheet tool is recommended to assist in selecting and planning maintenance activities. For a given project, this tool will predict the most cost-effective maintenance treatment (crack sealing, chip seal, microsurfacing or do nothing) that addresses existing surface distresses without causing moisture damage. The tool will also provide the optimal timing of the recommended maintenance treatment. The developed tool is implementation-ready and should be utilized by the Department to maximize savings to the state.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Pavement performance significantly depends on the effectiveness and timing of maintenance activities. Deferred maintenance increases the severity of distresses and leads to a more rapid decline of its condition. An effective maintenance program helps maintain riding quality, delays deterioration, and corrects pavement deficiencies. Maintenance activities include preventive and corrective maintenance *[1-2]*. Crack sealing is used by many states on a routine basis for preventive maintenance as shown in Figure 1. This treatment is commonly part of a comprehensive pavement preventative and maintenance program *[3]*.

Figure 1
Typical crack sealing application

Crack sealing prevents the ingress of water in the pavement structure, thus preventing the weakening of the pavement and delaying its deterioration. Years of service life may be added to the pavement at a relatively low cost, assuming that an appropriate sealant material is correctly installed at the right time in the pavement life *[4]*. Various studies demonstrated the cost effectiveness of crack sealing *[5-7]*. For example, the Province of Ontario reported that crack sealing can extend the service life of asphalt pavements by up to four years *[5]*.

In spite of these benefits, the use of crack sealing in Louisiana has been limited as earlier studies showed that the performance of this maintenance practice can be affected by the shallow groundwater table conditions in the state *[3]*. According to these studies, crack sealing can prevent water from escaping through the cracks and; therefore, cause an acceleration of asphalt concrete (AC) stripping in the overlay. Yet, the use of any impermeable treatment including overlays on top of a pavement with shallow groundwater table may cause the same problem *[8-9]*.

Literature Review

Crack sealing has been widely used by state highway agencies for preventive maintenance activities. It is a treatment technique where hot-poured bituminous-based materials are added into and/or above working cracks using pre-defined configurations. Crack sealing minimizes water penetration into the pavement, reduces traffic erosion, and prevents intrusion of incompressible materials into the crack *[10]*. Results from the Strategic Highway Research Program (SHRP) suggest that crack density and general conditions of the crack influence the success of crack sealing as shown in Table 1 *[4]*. Crack sealing is typically recommended when the cracks are moderate in density and exhibit low to moderate edge deterioration.

Table 1
Guidelines for selection of maintenance activity *[4]*

Crack / Density	Average Level of Edge Deterioration (% of crack Length)		
	Low (0 to 25)	Moderate (26 to 50)	High (51 to 100)
Low	Nothing	**Crack sealing**	Crack Repair[1]
Moderate	**Crack sealing**	**Crack sealing**	Crack Repair
High	Surface Treatment[2]	Surface Treatment	Rehabilitation

[1]Partial-depth patching, spot patching, etc.; [2]chip seals, slurry seals, etc.

A comprehensive review of the literature was conducted to provide the study with valuable information as related to the following topics:

- State practices in using crack sealants as a preventive maintenance activity;
- Field performance of crack sealing and other surface treatments;
- Cost benefit analysis of crack sealing and other surface treatments;
- Effects of shallow groundwater table on the performance of crack sealing and other surface treatments; and
- Louisiana Pavement Management System.

State of Practices in Using Crack Sealants as a Preventive Maintenance Activity

Crack Sealant Materials. Selection of the sealant material is a critical factor that influences the efficiency of crack treatment operations. Common available sealant materials are classified according to their manufacturing process and compositions as presented in Table 2.

Table 2
Common crack sealant materials *[4, 11]*

Material Group	Material Type	Example Product
Cold-applied thermoplastic bituminous materials	Liquid asphalt	Witco CRF
	Polymer modified liquid asphalt	Hy-Grade Kold Flo
Hot-applied thermoplastic bituminous materials	Asphalt cement	85-100 Penetration-Graded AC
	Fiberized asphalt	Kapejo BoniFibers+AC (AC-20)
	Asphalt rubber	Crafco AR2
	Rubberized asphalt	Crafco RS211
	Low-modulus rubberized asphalt	Meadows XLM
Chemically-cured thermosetting materials	Self-leveling silicone	Dow Corning 890-SL

Emulsified asphalt materials are specified in ASTM D 977-13, while hot-poured sealant materials are specified in ASTM D 6690-15, which classifies hot-poured sealant materials into four major groups according to their material specifications; see Figure 2 *[12]*.

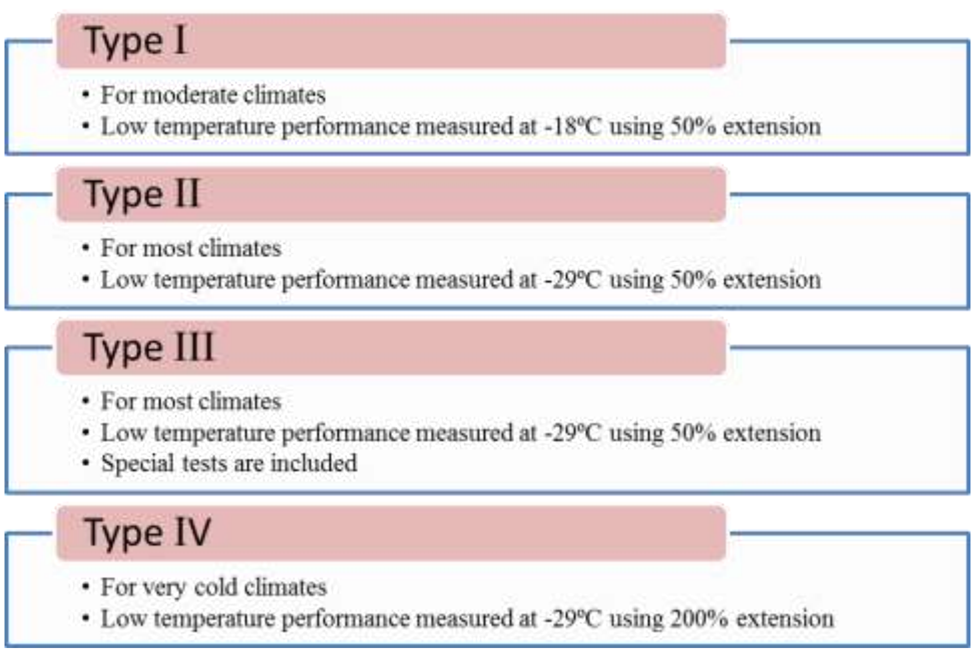


Figure 2
ASTM D6690 Sealant material types *[12]*

Sealant material type is selected according to the climatic conditions as suggested by ASTM D 6690. Once the sealant material is selected, it should be tested to verify that it has the desirable properties as described in ASTM D 5329-16, ASTM D 36/D36M-14, and ASTM D 6690-15 *[13-16]*. Recently, several studies examined the ASTM standards and reported that the field performance of hot-poured sealants does not correlate well with laboratory tests *[17-19]*. Therefore, extensive research effort was conducted to incorporate fundamental material properties in sealant characterization. In this context, Al-Qadi and co-workers published various journal articles, papers, and technical reports to develop a new grading system for hot-poured sealants called the *Performance-Based Grading System for Hot-poured Crack sealant [19]*. In this grading system, the material is defined by a Sealant Grade (SG) similar to the Superpave Performance Grade (PG) for asphalt binder with minor differences in test protocols and equipment.

Timing of Sealant Application. Even with the best materials, improper timing of sealant application will adversely affect its performance. It is therefore important to select proper timing for sealant application. Early studies recommended crack sealing application to be conducted during late fall or early spring time *[20]*. During this period, the cracks are adequately open due to low temperatures, the installation crews are available, and the ambient temperature would be within the temperature range specified by the manufacturer, which is usually between 40 and 70°F *[20]*. Similarly, the Federal Highway Administration (FHWA) reported that cracks shall be sealed during late fall or spring time, when the ambient temperature ranges between 45 to 65°F. Recent studies extended the ambient temperature range in which the sealant could be installed successfully to be between 40 and 80°F *[13, 21]*.

Crack Routing. In crack sealing, cracks are usually cut ahead of sealant placement through routing or sawing. Routing of cracks is more common among states, whereas sawing of cracks is only conducted by a limited number of states *[22]*. Crack sawing refers to sawing the surface cracks using a saw prior to crack sealant application, while crack routing refers to creating a reservoir centered over existing transverse working cracks using a pavement router or saw *[23]*. Several research studies have been conducted to evaluate the effectiveness of crack routing. Table 3 summarizes the findings of these studies.

Crack Preparation. Crack preparation is a key aspect of sealing operations performed immediately before sealant application to provide a clean and dry environment for the sealant to be placed. Typically, clean and dry cracks do not experience adhesion failures resulting from poor sealant adhesion to the sides of the crack in wet or dirty channels *[4, 13]*. Air compressor and hot-air lance (HAL) are common equipment used to clean the cracks before sealing *[13]*. Air-compressor uses high pressure compressed air to clean cracks from any foreign materials without significant impact on the channel moisture *[20]*. While the hot-air lance is a propane fired wand that is able to both clean the crack using compressed air, and dry the crack and the surrounding pavement using heat, and thus it is more effective than the standard air compressor *[4, 20]*.

Table 3
Crack routing effectiveness studies

Reference	General Recommendations
Eaton *[20]*	Routing should be avoided on pavements older than 6 years or less than 2.0 in. thick
Ponniah [*5]*	Rout and seal is not recommended in the following conditions: 1. Cracks are fatigue cracks (alligator type), and crack width is less than 1/8 in., 2. Crack density is 80-100% of the pavement or transverse cracks have less than 30 in. spacing, 3. Pavement condition is poor, or 4. Pavement thickness is less than 2 in.
Filice *[24]*	Pavement is not recommended for rout-and-crack sealing under the following conditions: 1. Alligator cracks, and crack width is less than 1/8 in. or more than 3/4 in. 2. Severe crack density, or 3. Pavement is being considered for rehabilitation. Pavement shall be routed under the following conditions: 1. Crack width is between 1/8 in. and 1/2 in. 2. Crack width between 1/2 in. and 3/4 in. should be evaluated to determine appropriateness. 3. Cracks are longitudinal, transverse or edge cracks.
Masson [*25]*	Routing on asphalt over concrete pavement created micro-cracks at the bitumen aggregate interface and within aggregates themselves.
Al-Qadi *[26]*	Based on a recent Illinois study conducted in seven different states, it was concluded that routing before crack sealing is recommended as an effective treatment technique for working cracks.

Placement Configuration Types. In crack sealing, the material could be added into the cracks using different configurations. These configurations are defined by (a) the level of the material with respect to the pavement surface when placed into the crack, and (b) the type of crack channel whether routed or non-routed *[13]*. Figure 3 illustrates the different configurations used in crack sealant application. The National Cooperative Highway Research Program (NCHRP) discussed the advantages and disadvantages of each treatment configuration and recommended the most appropriate configuration according to application conditions as shown in Table 4 *[13]*.

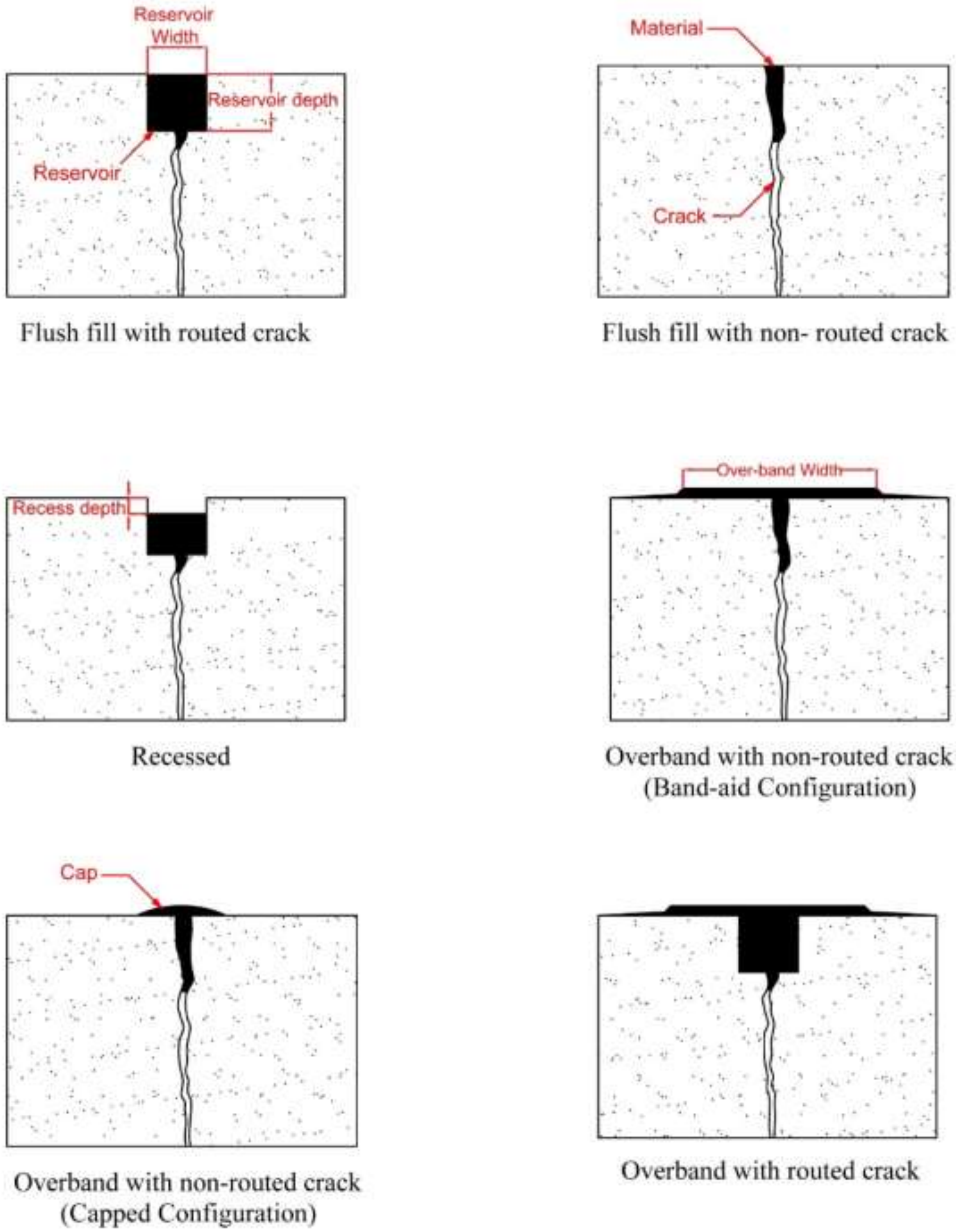


Figure 3

Different crack sealing configurations ***[4, 11, 13]***

Table 4
NCHRP recommended placement configurations *[13]*

Sealant placement configuration	Application Conditions
Recessed configuration	• Recommended 6-12 months prior to overlay placement to minimize the formation of any potential bumps when the sealant comes in contact with the hot overlay.
Overband configurations (maximum overband width of 3 in)	• Low-traffic roadways; • When traffic will be on the treatment immediately after application; • Shall not be used if an overlay is planned;
Flush fill configuration	• Recommended when microsurfacing or chip seal is to be placed on the pavement with no concern of bump formation;

Material Preparation and Placement. Prior to sealant placement, the sealant should be prepared and brought to application temperature. The manufacturer of any sealant provides recommendations for the product that should be followed to achieve the expected sealant performance. These recommendations include melting recommendations, minimum placement temperature, maximum safe heating temperature, and length of heating time. The user should be familiar with such recommendations and be able to follow them *[13]*. The equipment used in sealant preparation and placement primarily depends on the type of material used as follows *[4, 11, 13]*:

- Emulsion materials are generally applied using wheeled or hand-held pour pots or distributors equipped with gravity or pressure hoses for wand application;
- Chemically cured thermosetting materials are applied using silicone pump;
- Asphalt cement should be heated and applied using distributor or direct-heat kettle/melter; and
- Fiber-and rubber-modified asphaltic materials should not be heated using direct heat melter to avoid asphalt overheating; instead, they should be heated and mixed using an indirect-heat, agitator-type melter.

Finishing and Blotting. Once the sealant material is applied into the cracks, material finishing must be conducted using a squeegee to shape the material surface as desired *[4, 13]*. The type of squeegee differs according to the type of sealant used in the treatment process. For instance, cold-poured sealants require a rubber-faced squeegee, while hot-poured sealants necessitate all-metal squeegee as shown in Figure 4. Adequate amount of blotter material is applied immediately after the finishing process to protect the uncured crack treatment from tracking by traffic. Common blotter materials include blotter sand, release agent, and plastic/paper *[4, 13]*. A recent NCHRP survey indicated that most of the states do not use blotter materials (blotter sand, release agents or plastic/paper). Alternatively, dishwashing soap or toilet paper are used if tracking by traffic becomes a serious problem on a specific project *[13]*.

Figure 4

All-metal squeegee (on the left) vs. rubber-faced squeegee (on the right) *[13]*

Crack Sealant Failures. Crack sealant failures could be easily identified through visual inspection. These failures result from the excessive stresses a sealant undergoes as the crack opens and closes with temperature variations. These excessive stresses can be attributed to improper material selection or neglecting one or more of the construction considerations previously discussed *[27]*. Common sealant failures include the following *[4, 27-30]*:

1. <u>Adhesion loss, see Figure 5:</u> Separation of the sealant from the sides or bottom of the crack if the bond strength is too weak or the adhesive tensile stress created by crack movement is significantly large.

1. <u>Pull-out, see Figure 5:</u> The sealant material is pulled out of the crack by tire action.

2. <u>Cohesion loss, see Figure 6:</u> Tearing of the sealant material if it is not sufficiently elastic, the inter-particle bond within the sealant is very weak or the tensile stress developed by crack movement is too high.

3. Extrusive failure, see Figure 6: Occurs at high temperature when excessive compressive stress develops in the sealant, and the sealant is pushed above the pavement surface.
4. Intrusive failure, see Figure 7: This type of failure occurs when the sealant material extends, necks down, and fills with dirt and debris. In the subsequent compression cycle, this pocket of dirt tends to close. The closing action abrades the seal surface so that it fails in the following tension cycle.
5. Potholes: The crack is not completely sealed; therefore, water will penetrate into the pavement structure causing deterioration. Continued deterioration may cause pothole formation.
6. Spalls: The crack edges break away when the cohesive strength of the sealant is higher than the cohesive strength of the substrate.

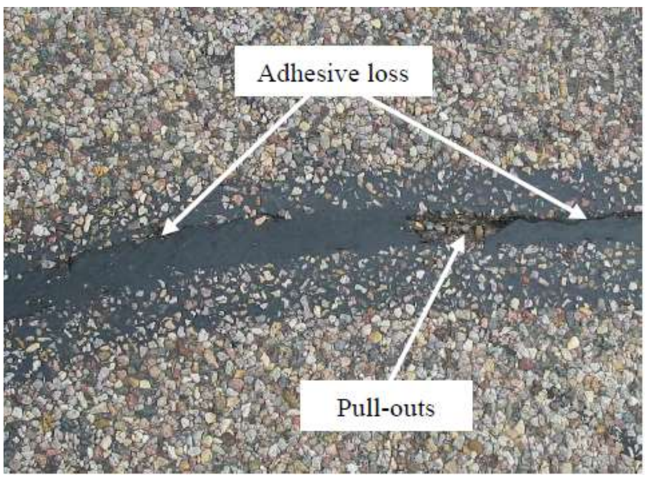


Figure 5

Sealed cracks showing two modes of failures: adhesive loss and pull-out *[29]*

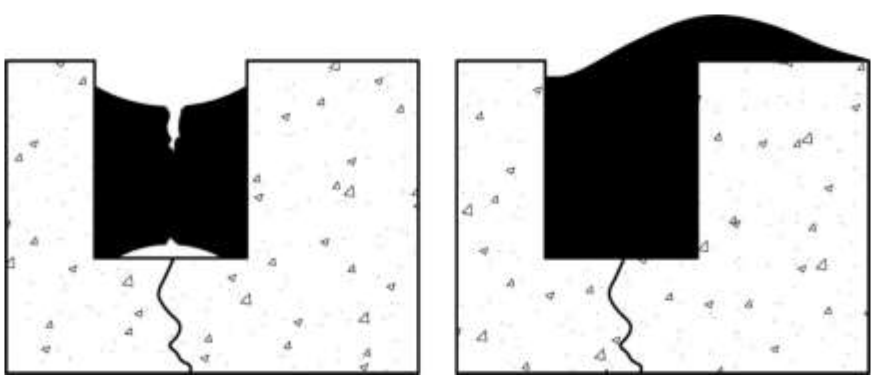


Figure 6

Schematic of cohesive failure (left) and extrusive failure (right) *[27]*

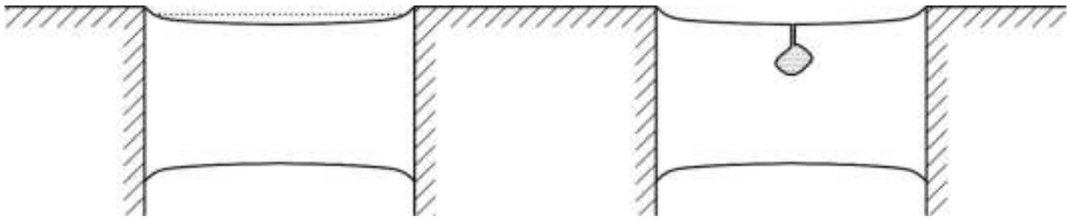


Figure 7
Schematic of intrusion failure *[30]*

Field Performance of Crack sealing and other Surface Treatments

As the case with any maintenance treatment, the most important part in crack sealing is the final performance of the product. Numerous studies were conducted over the past years to recognize the field performance of crack sealing and other surface treatments, namely, chip seal and microsurfacing.

Field Performance of Crack Sealing. Recently, different studies have been conducted to evaluate the field performance of crack sealing with a special focus on overall pavement conditions. In 1986, the Ministry of Transportation, Ontario, Canada, conducted a research study to assess the benefits of crack sealing in extending pavement service life (PSL). Thirty-seven sections were selected covering different climatic conditions, traffic levels, pavement age, and thicknesses. For each sealed section, an untreated segment was identified for comparative evaluation. Performance curves, in terms of pavement condition index, were drawn for sealed and untreated sections based on data collected during a 7-year monitoring period. The results indicated that crack sealing extends the PSL by at least two years, depending on traffic volume, environment, and pavement's original conditions *[5]*.

A research study was carried out by the Ohio Department of Transportation to evaluate field performance of crack sealing. Test sections were selected over the state including 57 counties. In each test section, 1000-ft. long subsection was left unsealed to serve as a control segment. Results indicated that crack-sealed pavements provided better performance than untreated pavements, in terms of pavement condition rating, on a five-year life cycle. Furthermore, it was reported that crack sealing could prolong the PSL by up to 3.6 years *[6]*.

Based on a national survey, Eaton indicated that 70% of the states that seal cracks reported an increase in PSL by at least three years *[20]*. The short-term effectiveness of crack sealing was evaluated in terms of the International Roughness Index (IRI). It was concluded that crack sealing offers an average reduction in IRI of 17 in. /mile *[31]*. Yet, other studies indicated that crack sealing has no significant impact on roughness *[32-33]*. An extensive investigation was conducted under the Long-Term Pavement Performance (LTPP) program to evaluate the field performance of different sealant materials. Key findings indicated that rubberized asphalt sealant material placed in a standard or shallow-recessed Band-Aid configuration provided the best field performance among other material types and placement configurations. Further findings indicated that sealant in cracks with low crack movement and low traffic performed better than sealants with high crack movement and traffic *[28]*.

Field Performance of Chip Seal. Several measures have been introduced to evaluate the short-term effectiveness of chip seal, which include performance jump, deterioration reduction level, and deterioration rate reduction *[31, 34]*. A study conducted by Haider and Dwaikat observed a 5 to 10% performance jump in IRI due to chip seal. They also reported that the rate of deterioration after treatment was higher for chip seal as compared to slurry seal, crack sealing, and thin overlays *[35]*. Labi and Sinha studied the effectiveness of chip seal for 35 pavement sections and observed that higher performance jumps are associated with the poor initial conditions of the pavement. Furthermore, the benefits of treatment activities applied on pavements with good to excellent initial conditions were negligible in terms of performance jumps *[34]*. However, other researchers have reported that performance jumps are not solely dependent upon the pre-treatment conditions of the pavement; however, they are significantly influenced by other endogenous and exogenous factors, such as traffic, age, type, and pavement class *[36]*.

Other studies were conducted to evaluate the long-term performance of chip seal. Ram and Peshkin studied the performance of the preventive maintenance program of the Michigan Department of Transportation (MDOT) and reported a service life extension of 4.3 to 6 years for single chip seal and 6.9 years for double chip seal applied on flexible pavements *[7]*. The study found that most of the preventive maintenance activities were performed on pavements in fair to good conditions. Another study by Kiefer et al. reported an increase of 4.1 years in service life when chip seal was applied on flexible pavements; yet, chip seal treatments experienced a reduction in service life extension when it was used with fog seal *[37]*. To verify the hypothesis that chip seal can be applied in a preventive mode, Mamlouk and Dosa evaluated the long-term effectiveness of this treatment based upon initial roughness conditions in four different climatic conditions. The increase in service life for smooth, medium, and rough pavements due to chip seal treatments were found to be 4-7 years, 2-3 years, and 0-1 years, respectively. The study concluded that for chip seal to be effective, it must be applied on pavements before surface distresses become significant *[38]*.

Field Performance of Microsurfacing. Louisiana's $6.3 million microsurfacing program is amongst the largest microsurfacing programs in the United States *[39]*. Louisiana has a humid subtropical climate, characterized by long, hot, humid summers with heavy rainfalls throughout the year where microsurfacing treatments primarily serve the purpose of waterproofing the pavement surface. Temple et al. investigated the performance of Louisiana's microsurfacing program in 2002 *[40]*. The study analyzed treated sections for 60 months and detected significantly fewer cracks and substantial reduction in rutting after treatment. However, this study assessed the effectiveness of microsurfacing holistically and did not provide insights into the factors affecting the performance of microsurfacing in Louisiana.

Labi et al. studied the long-term performance of microsurfacing applications in Indiana where it was found to extend pavement service life by 4 to 15 years *[41]*. Most of the studies have reported a treatment service life of 4 to 7 years if microsurfacing is applied properly *[40, 42-44]*. Microsurfacing was found to be most effective in addressing rutting as it reduced rutting by 90 to 96%, whereas it was only 7 to 27% effective in reducing the surface roughness of the pavement *[41, 45]*. Watson and Jared evaluated Georgia DOT's experience with microsurfacing as an economical alternative to conventional dense-graded resurfacing *[46]*. The study estimated about 5 to 7 years increase in service life for the Southeastern region of the US, where the cost of microsurfacing mix ranged from $1.07 to $1.20/m^2.

Cost Benefit Analysis of Crack Sealing and other Surface Treatments

Cost-benefit analysis of surface treatments refers to the process of adding all the costs associated with installing the material and comparing them with the service life of the treatment to obtain the maximum benefit from each maintenance dollar spent. This method is an important tool to assist in the selection of crack sealing materials and procedures by highway agencies *[4]*. There are several methodologies available for conducting the cost-benefit analysis for crack sealants, some of which can be very complex. Table 5 lists the most common methods used by researchers and highway agencies *[47-48]*.

Cost Benefit Analysis of Crack Sealing. Typically, the Equivalent Annual Cost (EAC) approach is used to evaluate the cost effectiveness of crack sealing because it is relatively simple and straightforward *[4, 47]*. However, other studies used the Life-Cycle Cost Analysis (LCCA) and Cost Effectiveness (CE) approaches to assess the economic benefits of crack sealing. A cost-benefit analysis was conducted by the Ministry of Transportation, Ontario, Canada, to assess the economic benefits of crack sealing. The CE and LCCA approaches were used to compare between two repair strategies. The first repair strategy consisted of a major rehabilitation activity using structural AC overlays, while the second repair strategy considered routing and sealing cracks in addition to the AC overlays. Findings indicated that alternative two was more cost-effective than alternative one *[5]*.

Table 5
Common cost-benefit analysis methods *[47-48]*

Method	Input	Output
Life–cycle cost analysis (LCCA)	1-Interest and inflation rates 3-Analysis period 4-Unit cost for treatment 5-Estimated life of treatment	Present value or equivalent uniform annual cost for each proposed treatment
Equivalent annual cost (EAC)	1-Unit cost for treatment 2-Estimated life of treatment	Unit performance life of treatment per cost
Cost-effectiveness analysis (CE)	Pavement performance curve	Area under the pavement performance curve is equivalent to effectiveness
Longevity cost index	1-Unit cost and life of the treatment 2-Present value of unit cost over treatment life 3-Traffic loading	Relates present value of cost of treatment to life and traffic

Rajagopal evaluated the cost-effectiveness of crack sealing using the LCCA approach and reported that crack sealing is cost-effective when applied to pavements with pre-treatment Pavement Condition Rating (PCR) between 66 and 80 *[6]*. Ram and Peshkin used the CE approach to evaluate the benefits and costs of different preventive maintenance treatments, including crack sealing. Results indicated that crack sealing was the most cost-effective treatment for flexible pavements. However, it was recommended that more than one economic measure should be used in selecting the most cost-effective maintenance strategy *[7]*. Similarly, Cuelho and Reed used the CE approach to establish the most economical and effective method of sealing cracks in Montana. Results identified the most cost-effective crack sealing material and the shallow and flush was the most cost-effective placement configuration *[49]*.

A cost-benefit analysis was conducted in Pennsylvania using the EAC and LCCA approaches to assess the benefits and costs associated with crack sealing and other preventive maintenance strategies. Results indicated that crack sealing is the most cost-effective treatment when applied relatively early in the pavement life *[50]*. Recently, a cost-benefit analysis was conducted in Illinois using the EAC and LCCA to select the most cost-effective sealing practice. Based on the findings, it was concluded that crack sealing is a cost-effective maintenance strategy *[51]*.

Cost Benefit Analysis of Chip Seal and Microsurfacing. Ram et al. studied the cost-effectiveness of MDOT's preventive maintenance program by evaluating the pavement service life extension, benefit area and benefit-cost ratios of the associated projects *[7]*. Crack sealing had the highest benefit cost ratios for flexible pavements, whereas microsurfacing was found to be the most cost-effective for composite pavements followed by crack sealing and double chip seals. However, the study concluded that only a single measure like cost effectiveness should not be used as the sole parameter in selecting the appropriate maintenance treatment activity. The study also used a simplified life cycle cost analysis approach to compare the benefits accrued from a Capital Preventive Maintenance strategy and a rehabilitation only strategy. The results indicated that a rehabilitation only strategy generated an average benefits of almost $265,000 per lane-mile for composite pavements and that the MDOT's CPM program for flexible pavements resulted in an average savings of almost $310,000 per lane-mile.

Tarefder et al. evaluated the cost-effectiveness of millings over virgin chips in terms of benefit area, Equivalent Uniform Annual Cost (EUAC), Benefit Cost (B/C) ratio, and Effectiveness Index *[52]*. All the measures indicated that, chip seals with milling had better economic benefits than chip seals without millings. Another study by Mamlouk et al. calculated the benefit-cost ratios based on the surface conditions of chip seal applied in four different climatic zones of the United States *[38]*. The results showed that smooth pavements had the highest benefit-cost ratios across all four climatic zones. Furthermore, results indicated that chip seals are more cost-effective in dry freeze and wet non-freeze zones as compared to the wet freeze and dry no-freeze zones.

The Pennsylvania Department of Transportation (PennDOT) conducted a study to assess the benefits and costs associated with microsurfacing and other pavement treatment strategies *[50]*. The study discussed several approaches in assessing the economic aspects of these treatment activities and reported that the approaches may result in slight differences in the outcomes, but the relative ranking of the treatments remain the same. Statewide surveys indicated that typical cost for microsurfacing and chip seal ranged from $2-4/yd^2$ and $1-2/yd^2$, respectively. The study also identified several other potential cost effective treatments and compared the equivalent annual cost (EAC) of these treatments with respect to the EAC's of thin overlays. Findings are summarized in Table 6. Another study by Hicks et al. also reported similar unit costs and expected life of the treated pavements as shown in Table 7 *[47]*.

Table 6

EAC based on the survey of state highway agencies *[50]*

Treatment type	Cost ($/yd^2)		Performance life (year)		EAC ($/yd2/year)			Cost ratio
	Low	High	Max	Min	Low	High	Ave	
Thin Overlay	2.55	5.50	12	7	0.21	0.79	0.50	1.00
Micro-surfacing	2.00	4.00	12	5	0.17	0.80	0.48	0.97
Crack Sealing	0.32	0.40	5	2	0.06	0.20	0.13	0.26
Chip Seal	0.90	1.78	8	4	0.11	0.45	0.28	0.56
NovaChip®	4.50	6.50	15	8	0.30	0.81	0.56	1.11
Fog Seal	0.25	0.60	5	2	0.05	0.30	0.18	0.35
Slurry Seal	1.50	3.00	6	4	0.25	0.75	0.50	1.00

Table 7

Typical unit costs and expected life of the preventive maintenance treatments *[47]*

Treatment	Cost/m^2	Cost/yd^2	Expected life of treatment		
			Min.	Average	Max
Crack Treatment	$0.60	$0.50	2	3	5
Fog Seals	$0.54	$0.45	2	3	4
Slurry Seals	$1.08	$0.90	3	5	7
Microsurfacing	$1.50	$1.25	3	7	9
Chip Seals	$1.02	$0.85	3	5	7
Thin Hot-Mix Overlay	$2.09	$1.75	2	7	12
Thin Cold-Mix Overlay	$1.50	$1.25	2	5	10

Rajagopal evaluated the cost-effectiveness of 225 chip seal and 214 microsurfacing projects *[43]*. The study found that on average chip seals are more economically beneficial than microsurfacing treatments when compared to the costs of thin asphalt. The treatments were also found more beneficial when applied to pavements having a prior PCI of 71 to 75. Results are shown in Figure 8.

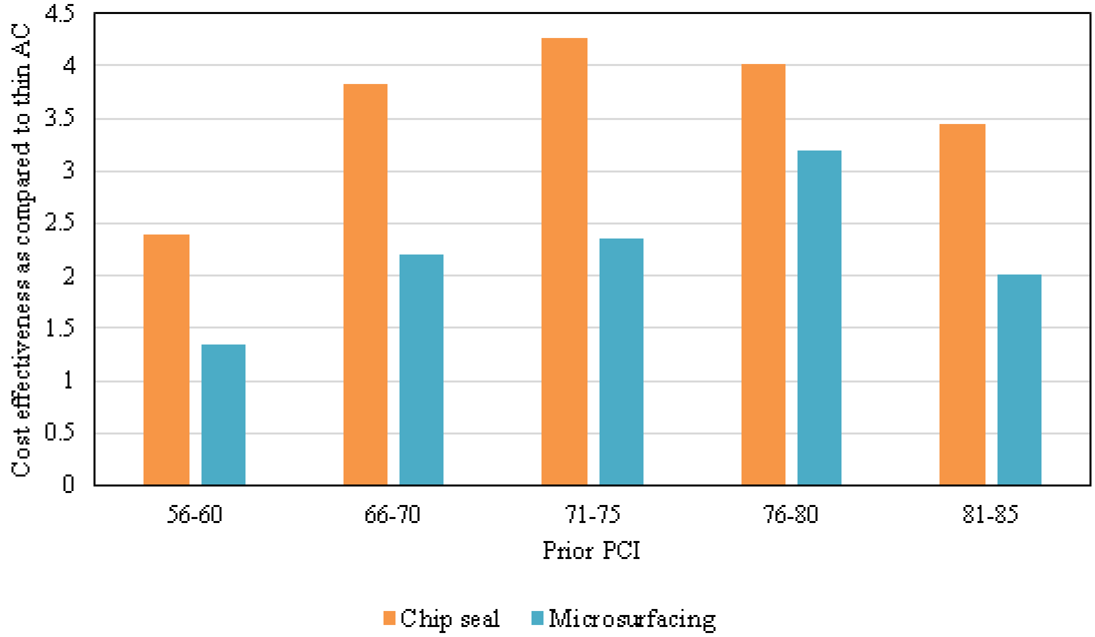


Figure 8
Relative cost effectiveness for chip seal and microsurfacing *[43]*

Effect of Moisture on the Performance of Crack Sealing and Surface Treatments

Crack sealing and surface treatments are widely used to prevent water from entering the underlying pavement structure. However, these treatments could be responsible for frequent failures and unsatisfactory projects if the surrounding moisture conditions are not adequately considered. These failures could be categorized into *[53-67]:*

a) **Treatment failure:** failure of the treatment itself under prolonged exposure to water, such as adhesive and cohesive failures.

b) **Pavement failure:** failure of pavement system covered with crack sealing or surface treatments due to entrapped water, such as stripping.

The literature herein summarizes various studies conducted to assess these failures under prolonged exposure of water.

Treatment Failure. A study conducted by Chew and Zhou examined the cohesive properties of three crack sealants under prolonged combination of water and heat *[53]*. The water-swelling rate, tensile stress, hardness, and elastic recovery were selected to account for the sealant cohesive properties. Results indicated that the three sealants passed the ASTM standards relating to the effects of heat, water, and/or Ultraviolet. However, they experienced high water-swelling and significant reductions in tensile strength, hardness and elastic recovery indicating that cohesive failure might occur for sealants in extreme conditions of combined water and heat *[53]*.

In 2011, Fini and Abu-Lebdeh indicated that various crack sealants performed differently when exposed to significant amounts of rain and humidity *[54]*. They introduced a water conditioning method and a test procedure to determine the bond strength of crack sealants when exposed to water. The blister test was used to calculate the tensile modulus and the Interfacial Fracture Energy before and after water conditioning. It was reported that water exposure reduced the sealant bond strength significantly; they also concluded that there was no significant difference between 8 and 12 hours of water conditioning *[54]*.

In 2015, Yeargin et al. developed an experimental plan to evaluate the impact of water conditioning on cohesive properties of crack sealants *[55]*. Three crack sealant types were considered and conditioned in water at 25°C for seven days. A Brookfield viscometer and a dynamic shear rheometer were used to measure the dynamic viscosity and complex shear modulus, respectively, for all crack sealants before and after water conditioning. The rotational viscometer results indicated that overall wet samples had lower viscosity than dry samples. Moreover, it was reported that shear susceptibility was insensitive to water conditioning. The analysis of dynamic shear rheometer results showed that the sealant gained elasticity immediately after water conditioning, while at longer conditioning time, it started to lose its elasticity gradually as shown in Figure 9. By day seven, it was observed that the top layer of the sealants deteriorated, which reflects considerable reduction in their cohesive and adhesive properties *[55]*.

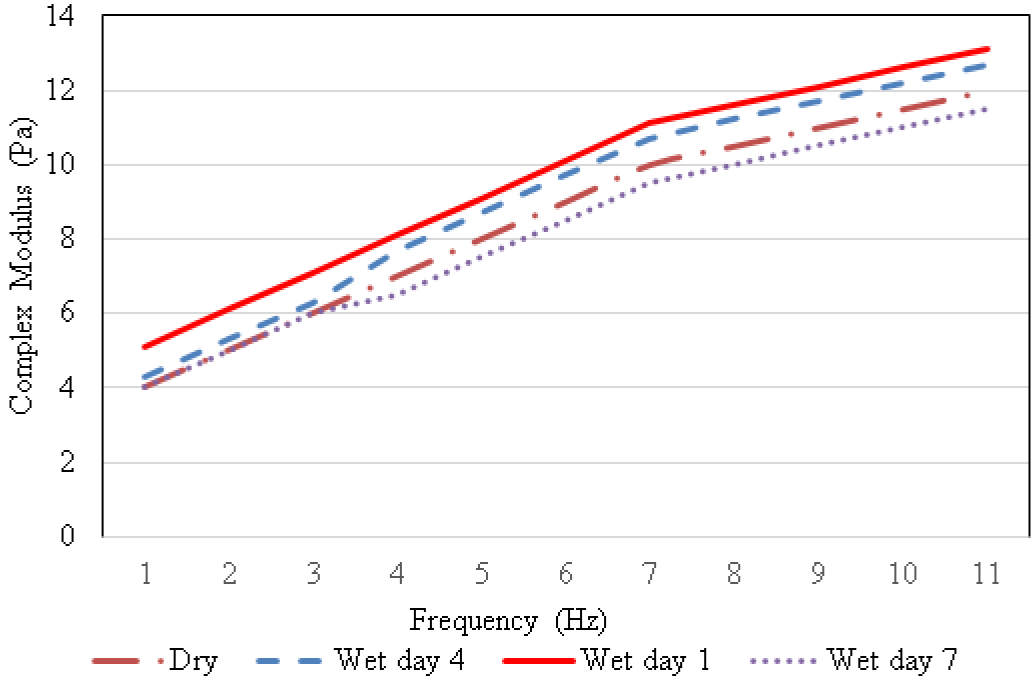


Figure 9

Complex shear modulus results for sealant A in dry and wet conditions *[55]*

An experimental investigation was carried out in North Carolina to evaluate the impact of moisture on the adhesive properties of three hot-poured crack sealants *[56]*. The selected crack sealants were Crafco Type I, Beram 195 (combination of Type II and III), and Crafco Type IV. These sealants are commonly used in hot, moderate, and cold climates, respectively. A direct adhesion test was carried out on the different sealant types before and after 22 hours of water exposure to measure their adhesion strength (peak load before failure) and fracture energy (energy required to break the adhesive bond). Furthermore, contact angles between droplet of water and surface of each sealant were measured before and after water conditioning at temperatures ranging between 40 and 80°C. As shown in Figure 10, the results of the direct adhesion test indicated that water reduced the fracture energy and adhesion strength for all the sealant types. However, reductions levels varied among sealant types, where B-195 experienced the highest reductions followed by Type IV, then Type I. The sessile drop findings showed that the B-195 sealant had the highest contact angle and the highest susceptibility to temperature changes. Based on the previous results, it was concluded that B-195 had the highest susceptibility to water, followed by sealant Type IV, while Type I had the least water-susceptibility *[56]*.

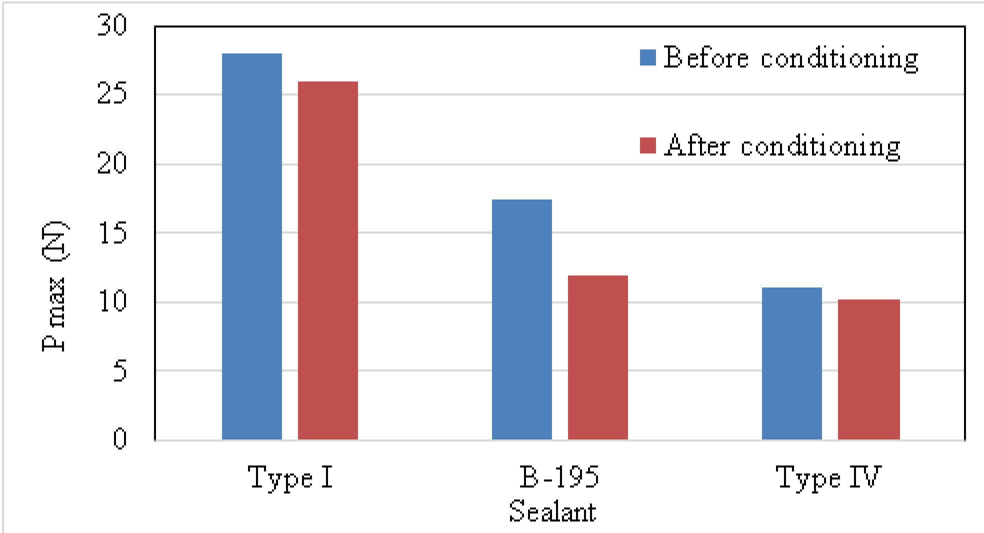


Figure 10

Load required to break the bond between sealant and the aluminum *[56]*

In 2016, Ahmed et al. examined the impact of water on the chemical and rheological properties of six hot-poured crack sealants widely-used in cold, moderate, and hot climates *[57]*. To do so, the authors conducted four laboratory tests on dry and wet samples of the six different sealants, namely, dynamic shear rheometer, bending beam rheometer, direct adhesion test, and Fourier transform infrared spectroscopy (FTIR). For most of the tested sealants, the dynamic shear rheometer showed that the relaxation time increased after water conditioning. This means that when the sealant is exposed to water, the time it takes for the stress to dissipate increases, when a constant strain is applied on the sealant indicating slow stress recovery. Furthermore, the dynamic shear rheometer results indicated reductions in the modulus of elasticity of most of the wet sealants due to the damaging effect of water on the sealant rheological properties. The analysis of bending beam rheometer results indicated that some of the sealants had faster displacement recovery after water conditioning, this was attributed to their high resistance to low temperature climate. The results of direct adhesion test showed significant reductions in both peak load and fracture energy when all the sealants were exposed to water indicating that adhesion failure of crack sealants is accelerated in the presence of water. Fourier transform infrared results revealed the presence of oxygen bond after water conditioning indicating higher aging extent. Based on these results, a ranking of sealant's chemical and physical abilities was performed for the six sealants to determine the best sealant in terms of low susceptibility to failure after water exposure *[57]*.

Pavement Failure. As early as 1949, McKesson recognized the detrimental effects of seal coats when entrapment of moisture occurs *[58]*. Ground water and water entering the roadbed from the shoulders, ditches, and other surface sources, are carried upward underneath the pavement by capillary action. Above the capillary fringe, water moves as a vapor and, if unimpeded at the surface, it passes to the atmosphere; this is known as drainage by evaporation. If the seal coat constitutes a vapor seal, the water condenses beneath the surface in cool weather. When the pavement absorbs solar heat, the water is again vaporized and, if not free to escape, significant vapor pressure results. This pressure forces the moisture up into the pavement and through the surface. Blistering in asphalt pavements, shown in Figure 11, is a well-known example of the effect of entrapped moisture and moisture vapor *[58]*.

Figure 11
Blistering in asphalt pavements *[58]*

McKesson emphasized the drawbacks of seal coats if constructed on roadways passing through low areas with shallow groundwater levels. Under such conditions, water vapor condenses under the surface and softens the base layer and subgrade soil. Furthermore, the pavement would experience accelerated rutting and alligator cracking due to entrapped moisture beneath the surface. In a trip over 6,500 miles of roads in nine states, it was observed that hundreds of pavement sections adjacent to fields or low areas, experienced serious distresses resulting from vapor resistant seals *[58]*.

In 1985, Kennedy supported McKesson's hypothesis, and reported that surface sealing could prevent the evaporation of water that moves upwards through the pavement *[59]*. This conclusion was based on frequent cases in Texas and other states, in which a surface seal was applied on an existing pavement resulting in subsequent stripping. Similar conclusions were reported in Colorado and Nebraska, as they experienced stripping in their asphalt pavements due to water trapped underneath seal coats *[60]*.

A research effort was conducted in Pennsylvania to study the stripping phenomenon considering the subsurface drainage in the total pavement system *[61]*. The authors presented three case histories of water damage to asphalt overlays constructed over rigid pavements during a period of 10 years. Samples of pavement layer were obtained for field observations. The in-situ observations seemed to support McKesson's findings in many cases when the pavement was impervious as water and/or water vapor were entrapped underneath the pavement surface causing severe stripping as shown in Figure 12.

Figure 12
Pavement stripping in Pennsylvania *[61]*

In recent years, a study was conducted in Texas to evaluate the advantages and disadvantages of underseal application, which refers to placement of a seal coat prior to asphalt overlay *[63]*. The study included (a) districts' survey, to determine the successes and failures of underseal applications, and (b) nine case histories of underseal performance. The survey respondents indicated that one of the major problems experienced by underseals is trapping water in the lower asphalt layer causing it to strip, and therefore some of them cautioned using underseals if the underlying pavement is prone to stripping. Similarly, one of the case studies verified these findings.

In 2013, district surveys, laboratory tests, coring, and field tests were carried out in Minnesota to determine the reasons for stripping failure in AC treated with chip seals shown in Figure 13. The survey results indicated that more than 60% of respondents experienced stripping under chip seals. Based on laboratory testing, the authors suggested that stripping in AC was caused by high air voids or low density. Consequently, they offered preliminary recommendations including the use of fog seal instead of chip seal for existing roads with low density and high air voids. They believed that fog seals could prevent water infiltration into the pavement but would allow water vapor to escape through the surface. However, they emphasized the need of additional laboratory tests to validate this recommendation *[64]*.

Figure 13
Stripping failure in HMA treated with chip seal [*64]*

In 1986, the Texas Department of Transportation (TxDOT) sponsored a research project to investigate stripping and moisture damage in hot mix asphalt pavements treated with antistripping agents *[65]*. Field test sections were built in eight districts of the TxDOT and treated with antistripping agents. In District 13 (Victoria), the asphalt layer treated with different antistripping agents was covered with a 0.4-in. layer of micro-surfacing. The field test sections were monitored for signs of distress during the research study. Finally, core samples were obtained from the test sections for laboratory testing. The results indicated that all the test sections in District 13 experienced severe stripping in the underlying layer (the untreated layer under the test layer treated with antistripping agent) possibly due to the moisture entrapped in that layer.

The Colorado Department of Transportation (CDOT) conducted a research study to investigate the reasons behind pavement failure in Vasquez Boulevard in Commerce City *[66]*. This failure occurred shortly after a major rehabilitation project including 2-in. milling followed by 2-in. stone matrix asphalt (SMA) overlay. Based on the forensic investigation, it was concluded that the milled surface was exposed to about 7.5 in. of precipitation during the months of planning and paving. When the SMA overlay was placed, it acted as a moisture barrier where moisture was entrapped leading to asphalt failure. The authors also indicated that similar occurrences in Virginia and Georgia showed moisture trapped in the bottom layers may lead to premature pavement failure.

FHWA sponsored a research study to evaluate the benefits of preventive maintenance treatments, and to describe the application process for these treatments *[3]*. One of the major findings of this study indicated that crack sealing and patching can be detrimental to the performance of open graded mixes. Generally, these mixes allow water to drain through the material. Therefore, sealed cracks and patches at the pavement edges can create a dam-like structure in the surface, which may prevent the flow of water and lead to stripping failure. It was also found that sealing cracks while there is moisture inside the pavement structure can accelerate stripping. The most recent pavement design guide issued by TxDOT in 2016 mentioned that stripping usually starts after placement of new overlays *[67]*. Therefore, it is advisable to evaluate the existing material for stripping susceptibility. Similarly, the existing asphaltic layers should be evaluated in the laboratory for stripping potential before surface treatments are applied. In general, a surface treatment will seal off the vertical escape of moisture migrating upward out of a pavement, which can cause accelerated stripping in the existing AC layer beneath the seal *[67]*.

Pavement Performance Indicators in Louisiana Pavement Management System

In Louisiana, crack sealing activities are captured via the Maintenance Management System's work orders, while the other treatments are primarily performed under one of the pavement preservation programs with contract forces. Pavement performance data are reported in the Louisiana Department of Transportation and Development (DOTD) Pavement Management System (PMS) for the period ranging from 1996 to 2015. These data are based on pavement condition measurements that are collected biennially using the Automatic Road Analyzer (ARAN®) system that provides a continuous assessment of the road network *[68]*. Video crack surveys are available for each state highway in Louisiana and were reviewed using VisiData™ software *[68]*. Collected data are reported every 1/10th of a mile (log mile) and are analyzed to calculate different distress indices on a scale from zero to 100 (100 being perfect conditions).

For flexible and composite pavements, the Random Cracking Index (RCI) encompasses all random cracks, which include thermal transverse, reflective transverse, longitudinal, block, and cement-treated reflective cracks. RCI is calculated as follows *[69]*:

$$RCI = Min\{100, Max(0, 100 - DP_L - DP_M - DP_H)\} \quad (1)$$

where,

DP = deduct point due to random cracks; and
Subscripts L, M, and H= low, medium, and high severity of the cracks, respectively.

The Roughness Index (RFI) is expressed on a scale from zero to 100 with 100 representing the case with a smooth pavement. It is related to IRI as follows:

IRI (in/mile) = (100 - RFI) * 5 + 50 (2)

The rutting index (RTI) is expressed in a scale from 0 to 100 with 100 representing the case with no rutting. This index is calculated as follows:

If (R_AVG>=0 and R_AVG<0.125) RTI=100

If (R_AVG>=0.125 and R_AVG<1.375) RTI=-80*(R_AVG) + 110

If (R_AVG>=1.375) RTI=0 (3)

where,
RTI = rutting index; and
R_AVG= average rut depth in the pavement segment reported in inch.

For flexible pavements, the composite index (PCI) is calculated using the following equation:

PCI = MAX (MIN (RNDM, ALCR, PTCH, RFI, RTI), {AVG (RNDM, ALCR, PTCH, RFI, RTI) – 0.85 STD (RNDM, ALCR, PTCH, RFI, RTI)}) (4)

where,
RNDM = random cracking index;
ALCR = alligator cracking index;
PTCH = patch index;
RFI = roughness index;
RTI = rutting index; and
STD = standard deviation.

Pavement Performance as a Function of Time

Several studies have used a polynomial approach to model pavement conditions *[31, 50, 69]*. In this study, it was assumed that both pre and post-treatment conditions could be represented by polynomial models as depicted in Equations (5) and (6); see Figure 14:

$$f_{pre}(t) = a_1 t^2 + b_1 t + c_1 \quad (5)$$
$$f_{post}(t) = a_2 t^2 + b_2 t + c_2 \quad (6)$$

where,
a_1, b_1, c_1, a_2, b_2 and c_2 = fitting parameters related to pavement conditions and deterioration

rates over time for pre and post-treatment performance models; and
t = Time in years.

According to the model, the conditions of a pavement will deteriorate over time following curve A-C as shown in Figure 14; however, if any treatment is applied at time t_i (point B), the pavement condition index will increase to point D. After that, the deterioration pattern will follow the curve DE. The time is set equal to zero at point D for the post-treatment performance curve.

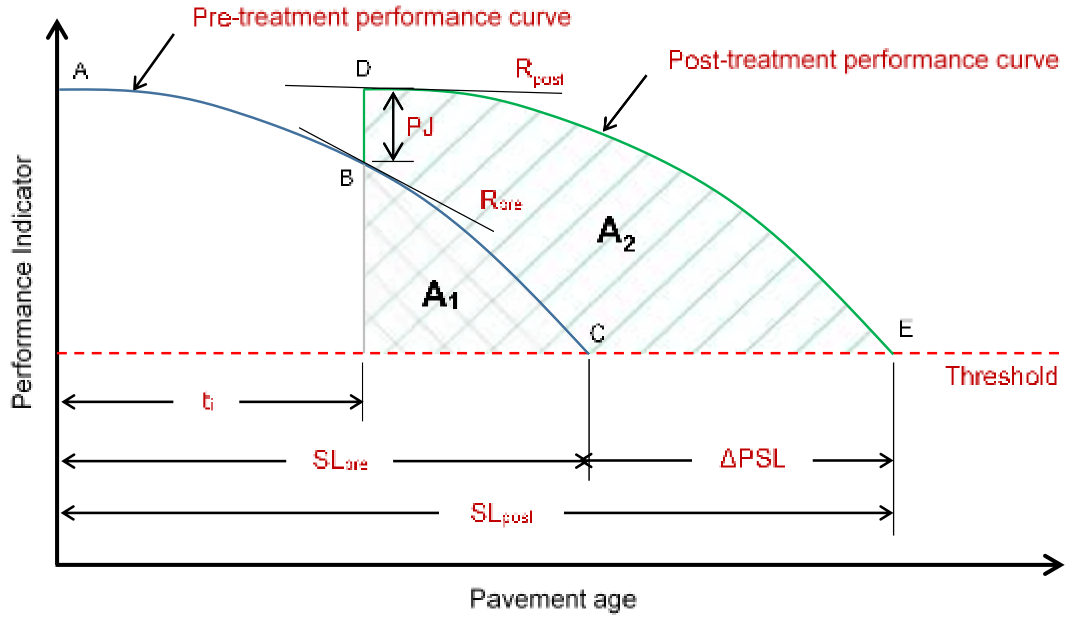


Figure 14
Pre and post-treatment performance curves due to treatment application

Measures of Effectiveness

Several measures have been developed to evaluate the short (immediate) and long-term effectiveness of maintenance treatments. These measures could be classified into short and long-term measures as shown in Table 8. These measures were used in this study to evaluate the field performance of the maintenance treatments and are described in the following sections.

Table 8

Common pavement performance measures *[6, 41, 70,71]*

Pavement Performance Measure Class	Pavement Performance Measure	Abbreviation
Short-term	Performance Jump	PJ
	Deterioration Rate Reduction	DRR
Long-term	Effectiveness	EF
	Average Performance Gain	APG
	Increase in Pavement Service Life (PSL), compared to the same section before treatment	ΔPSL
	Increase in Pavement Service Life (PSL), compared to a nearby untreated section	PSL*

Performance Jump (PJ). Performance Jump (PJ) is the immediate improvement in pavement conditions after applying the surface treatment and could be calculated by subtracting the first collected index after treatment application from the last index before treatment application *[70]*. The PJ could be visualized as the distance BD in Figure 14.

Deterioration Rate Reduction (DRR). Deterioration Rate Reduction (DRR) refers to the slowing down of the pavement deterioration. This can be estimated as the difference between the slope of the post-treatment performance curve just after treatment application (R_{post} in Figure 14) and the slope of the pre-treatment performance curve just before the treatment application (R_{pre} in Figure 14) *[71]*. This could be described as follows:

$$R_{pre} = \frac{df_{pre}(t)}{dt}\bigg|_{t=t_i} = 2a_1 t_i + b_1 \qquad (7)$$

$$R_{post} = \frac{df_{post}(t)}{dt}\bigg|_{t=0} = b_2 \qquad (8)$$

$$DRR = R_{post} - R_{pre} \qquad (9)$$

Effectiveness (EF). Effectiveness (EF) is the increase in average pavement conditions over the long-term due to treatment application *[41]*. For a treated section, the average pavement conditions over the service life (P_{AVG}) can be obtained as follows:

$$P_{AVG} = \frac{1}{n_c}(y_0 + y_1 + \cdots + y_n) \tag{10}$$

where,

y_0 = Pavement condition after treatment;

$y_1, y_2, .. y_{n-1}$ = Pavement condition at different years after treatment;

y_n = Pavement condition at the end of service life after treatment; and

n_c = Number of years the pavement condition was measured after treatment.

Effectiveness is the percentage change in average pavement conditions due to treatment application relative to the pretreatment conditions of the pavement as follows:

$$EF = \left(\frac{P_{AVG} - P_{INI}}{P_{INI}}\right) \times 100 \tag{11}$$

where,

P_{INI} = Pre-treatment condition of the pavement in terms of performance indicators.

Average Performance Gain (APG). Figure 15 illustrates the method used to compute the Average Performance Gain (APG) *[6]*. The figure shows two treated and untreated performance curves with exactly the same pre-treatment condition of the pavement at year 2003 where the treatment was applied in 2004. First, the performance gain should be calculated for each of years 2004, 2005, 2007, and 2009 as the difference in performance indicator between both curves. Finally, the APG is the average of these four values.

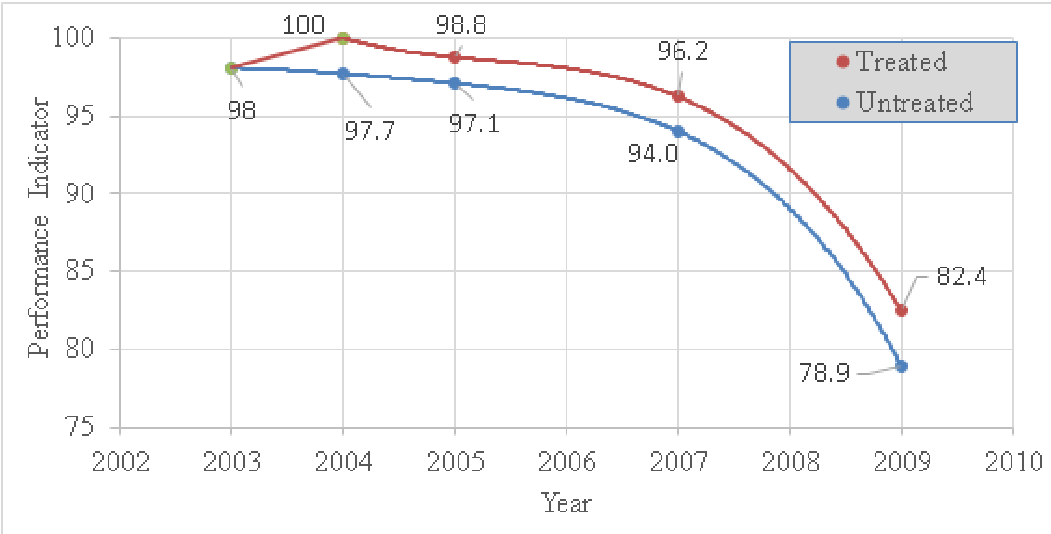


Figure 15
Deriving the Average Performance Gain (APG)

Increase in PSL, Compared to the Same Section before Treatment (ΔPSL). The pre and post-treatment performance curves will reach a specific threshold at different times as shown in Figure 14. The following equations are used to calculate the increase in PSL (ΔPSL):

$$SL_{pre} = \frac{-b_1 - \sqrt{-b_1^2 - 4a_1(c_1 - TV)}}{2a_1} \tag{12}$$

$$SL_{post} = \frac{-b_2 - \sqrt{-b_2^2 - 4a_2(c_2 - TV)}}{2a_2} + t_i \tag{13}$$

$$\Delta PSL = SL_{post} - SL_{pre} \tag{14}$$

where,

SL_{pre} = Pavement age with no treatment to the threshold;
SL_{post} = Pavement age with treatment to the threshold;
TV = Threshold pavement condition index; and
t_i = Pavement age; in years, at the treatment date.

Increase in PSL, Compared to a Nearby Untreated Section (PSL*). PSL* could be defined as the increase in the pavement service life after treatment application, when compared to an untreated segment as illustrated in Figure 16 *[6]*.

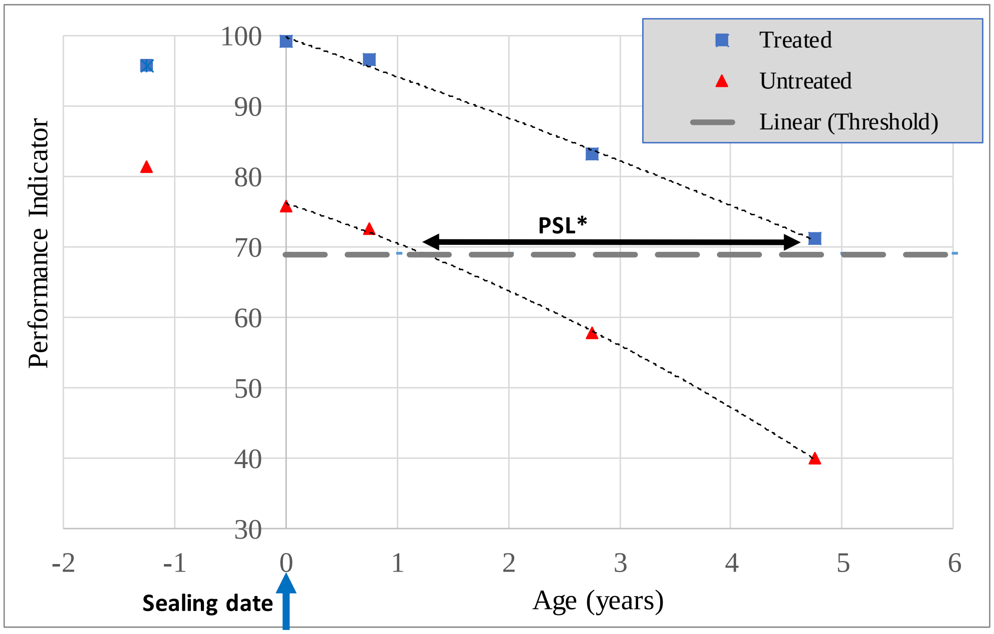


Figure 16
Deriving the PSL*

Measures of Cost-Benefit Analysis

The Equivalent Annual Cost (EAC), Life-Cycle Cost Analysis (LCCA), and Cost Effectiveness (CE) approaches were used in this study to evaluate the cost effectiveness of the maintenance treatments. A description of these measures is presented.

Equivalent Annual Cost (EAC). The EAC for a specific maintenance treatment is calculated as follows *[50]*:

$$\text{Equivalent Annual Cost (EAC) of maintenance treatment } = \frac{\text{Unit cost (\$/lane}-\text{mile)}}{\Delta\text{PSL (years)}} \quad (15)$$

Life Cycle Cost analysis (LCCA). LCCA is an engineering economic analysis technique to assess the overall long-term economic viability of competing project alternatives *[72]*. The most common indicators of LCCA include B/C ratio, Net Present Value (NPV), and EUAC *[73]*. The equation for NPV is *[74]*:

$$\text{NPV} = \text{IC} + [\textstyle\sum_{k=1}^{N} \text{PMC}_k \frac{1}{(1+i)^{nk}}] - [\text{SV}\frac{1}{(1+i)^{ne}}] \quad (16)$$

where,
IC= initial cost;
k= year of expenditure;
N= number of future costs incurred over the analysis period;
PMC_k = maintenance treatment cost at year k;
i= discount rate;
nk= number of years from the initial construction to the k^{th} expenditure;
SV= salvage value; and
ne= analysis period in years.

The equation for EUAC is *[74]*:

$$\mathrm{EUAC} = \mathrm{NPV} \times [\frac{i(1+\mathrm{i})^{\mathrm{n}}}{(1+\mathrm{i})^{\mathrm{n}}-1}] \quad (17)$$

where,
i= discount rate; and
n= years of expenditure.

In the B/C technique, the benefits of the maintenance treatment is quantified in monetary terms, through comparing the performance of the original AC overlay without any maintenance activity with the performance of the AC overlay after maintenance treatment application *[50]*. Hence, the B/C is calculated as follows:

$$\frac{\mathrm{B}}{\mathrm{C}} = \frac{\Delta\mathrm{EUAC}}{\mathrm{EUAC_{pvc}}} = \frac{\mathrm{EUAC_{do\ nothing}} - \mathrm{EUAC_{treatment}}}{\mathrm{EUAC_{pvc}}} \quad (18)$$

where,
ΔEUAC= net benefit of the maintenance treatment;
EUAC do nothing= EUAC of the original AC overlay due to "do nothing";
EUAC treatment= EUAC with application of the maintenance treatment; and
EUAC pvc= EUAC due to the cost of preservation.

The equations used to calculate $\mathrm{EUAC}_{\text{do nothing}}$, $\mathrm{EUAC}_{\text{treatment}}$, and $\mathrm{EUAC}_{\text{pvc}}$ can be found elsewhere *[75]*.

Cost-Effectiveness (CE). The CE of a maintenance treatment is defined as the ratio or percentage of treatment net benefits (TNB) to the treatment unit cost as follows *[43]:*

$$CE = \frac{TNB}{Unit\ cost\ of\ the\ treatment\ (\$/mile)} * 100 \quad (19)$$

The Treatment Net Benefits (TNB) is calculated as the increased area under the performance curve due to the treatment activity. According to Figure 14, TNB can be expressed as:

$$TNB = A_2 - A_1 \tag{20}$$

$$A_2 = \int_0^{SL_{post}-t_i} \left(f_{post} - TV\right) dt$$

$$A_2 = \frac{a_2}{3}\left(SL_{post} - t_i\right)^3 + \frac{b_2}{2}\left(SL_{post} - t_i\right)^2 + (c_2 - TV)\left(SL_{post} - t_i\right) \tag{21}$$

$$A_1 = \int_{t_i}^{SL_{pe}} \left(f_{pre} - TV\right) dt$$

$$A_1 = \frac{a_1}{3}\left(SL_{pre} - t_i\right)^3 + \frac{b_1}{2}\left(SL_{pre} - t_i\right)^2 + (C_1 - TV)(SL_{pre} - t_i) \tag{22}$$

where,

A_2 = Area enclosed between post-treatment performance curve and threshold value; and

$A1$ = Area enclosed between pre-treatment performance curve and threshold value.

OBJECTIVES

This study aims at quantifying the performance and benefits of using crack sealing and other impermeable surface treatments (chip seal and microsurfacing) under various groundwater table conditions and developing a user guideline for applying impermeable surface treatments to Louisiana highways. The following key objectives were achieved:

- Evaluate the field effectiveness of crack sealing and other surface treatments;
- Evaluate the effect crack sealing and other surface treatments on moisture damage under various groundwater table conditions; and
- Evaluate the cost-efficiency of crack sealing and other surface treatments.

SCOPE

Measurements from a field experiment conducted by the research team in District 58 were analyzed to evaluate the effect of groundwater and other parameters on the performance of crack sealing. Furthermore, the research team analyzed PMS data collected in all the districts from 2003 to 2015 to quantify the short and long-term effectiveness of crack sealing, chip seal, and microsurfacing. To facilitate implementation of the results, a user-friendly tool was developed in the form of a spreadsheet that could be used by the Department during the planning and design of maintenance activities.

METHODOLOGY

To achieve the study objectives, the research activities were divided into 11 main tasks. These tasks are described briefly in the following sections.

Review of DOTD State-of-the-Practice

The research team conducted a comprehensive survey to gather information from districts and cities in Louisiana as related to the current practices in using crack sealants and other impermeable surface treatments and their effectiveness as a preventive maintenance activity. The research team also contacted practitioners in the districts to gage opinions and experiences that have not been formally published on this topic and to understand the decision processes, which are used to determine when crack sealing and other impermeable surface treatments are selected. Furthermore, a project identification survey card was sent to district engineers to identify projects in which crack sealants and other impermeable surface treatments have been used. This card was considered as a first step in collecting relevant performance and cost data; it was sent to the nine districts in Louisiana. The research team worked with the LTRC staff to ensure that a thorough response for the survey is obtained from all the districts in the State.

Laboratory Evaluation of Crack Sealant Materials

The research team conducted a laboratory evaluation of the most common sealant materials in Louisiana to ensure their suitability for hot and humid climate such as the one encountered in the state. The two most common sealant materials in Louisiana are hot-poured rubberized asphalt (manufactured by Crafco) and cold-applied asphalt emulsion (CRS-2). Figure 17 shows both crack sealant materials as constructed in District 58.

Figure 17
Hot-poured rubberized asphalt (left) and asphalt emulsion (right) in District 58

ASTM D 6690-15 Testing of Rubberized Asphalt

The ASTM D 6690-15 specification tests were conducted on the hot-poured rubberized asphalt. These tests include cone penetration, resilience, softening point, and bond tests. Before conducting these tests, the sealant samples were prepared in accordance with ASTM D 5167-13, *Standard Practice for Melting of Hot-Applied Joint and Crack Sealant and Filler for Evaluation,* as shown in Figure 18. After sample preparation, the cone penetration, resilience, and bond tests were conducted in accordance with ASTM D 5329 – 16, *Standard Test Methods for Sealants and Fillers, Hot-Applied, for Joints and Cracks in Asphalt Pavements and Portland Cement Concrete Pavements,* while the softening point test was conducted in accordance with ASTM D 36/D36M −14, *Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus).* Figure 19 shows details of the test procedure. Since the rubberized asphalt sealants used in Louisiana are Type II (refer to Figure 2), the results of these four tests were compared against the standard specifications for Type II materials in the ASTM D 6690-15, *Joint and Crack Sealants, Hot Applied, for Concrete and Asphalt Pavements.*

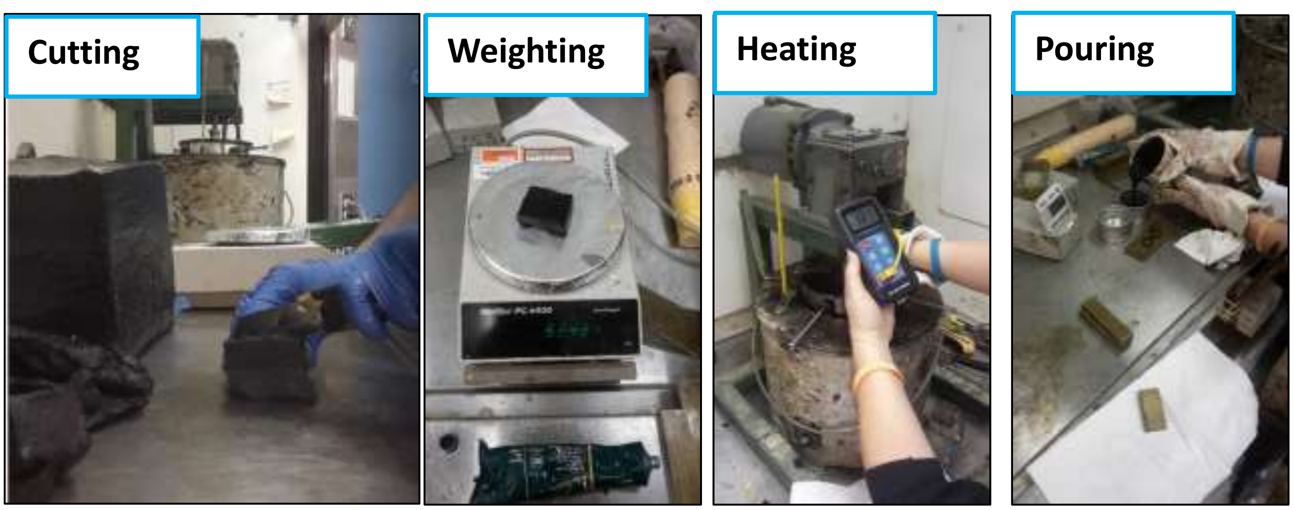


Figure 18
Main steps followed in crack sealant sample preparation

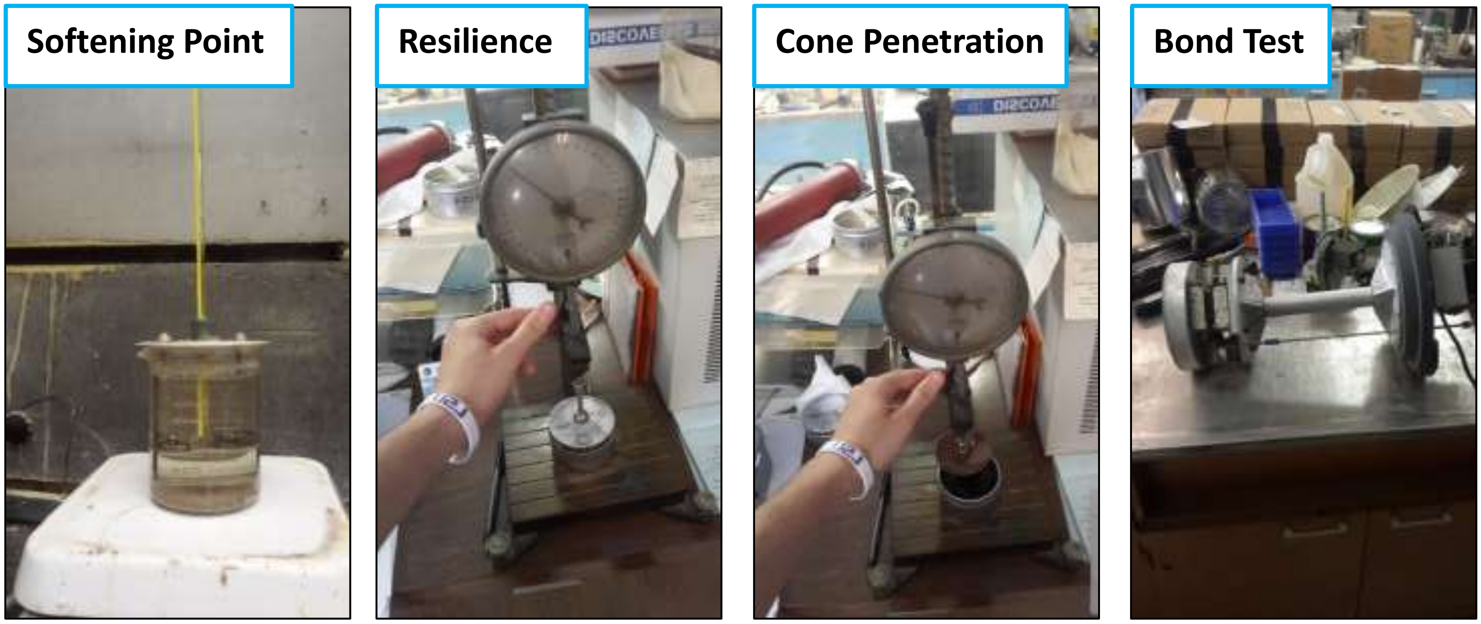


Figure 19
ASTM D 6690-15 laboratory tests

Performance Grading of Hot-Poured Rubberized Asphalt and Asphalt Emulsion

The research team complemented the ASTM tests with Performance Grading (PG) evaluation of both crack sealant types. For the asphalt emulsion, the residue was obtained by the evaporation method according to AASHTO T 59, *Standard Method of Test for Emulsified Asphalts.* The residual emulsion and the rubberized asphalt binder were short-term aged by pouring 35g of sample in each glass container and placing it in the Rolling Thin Film Oven (RTFO) at a temperature of 163 ± 1.0°C with the air flowing at 4000 ± 300 mL/min and the carriage rotating for 85 minutes. Long-term aged samples were then obtained by pouring 50 ± 0.5g of the RTFO aged samples into each of the stainless steel pan and conditioning in the Pressure Aging Vessel (PAV) at a temperature of 100°C and a pressure of 2.1 MPa for 20 hours. After that, the following PG tests were performed on the residual emulsion and the rubberized asphalt binder:

1. Dynamic Shear Rheometer (DSR) for the (a) original binder/emulsion residue, (b) RTFO aged sample, and (c) PAV aged sample in accordance with AASHTO T 315, *Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR).*

2. Bending Beam rheometer (BBR) for the PAV aged sample in accordance with AASHTO T 313, *Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR).*

In order to ensure repeatability of the test results, three replicates were conducted in each test and the average value was reported. The results were compared with the specifications in AASHTO M 320, *Standard Specification for Performance-Graded Asphalt Binder*. Figure 20 illustrates the sample preparation procedures and PG testing.

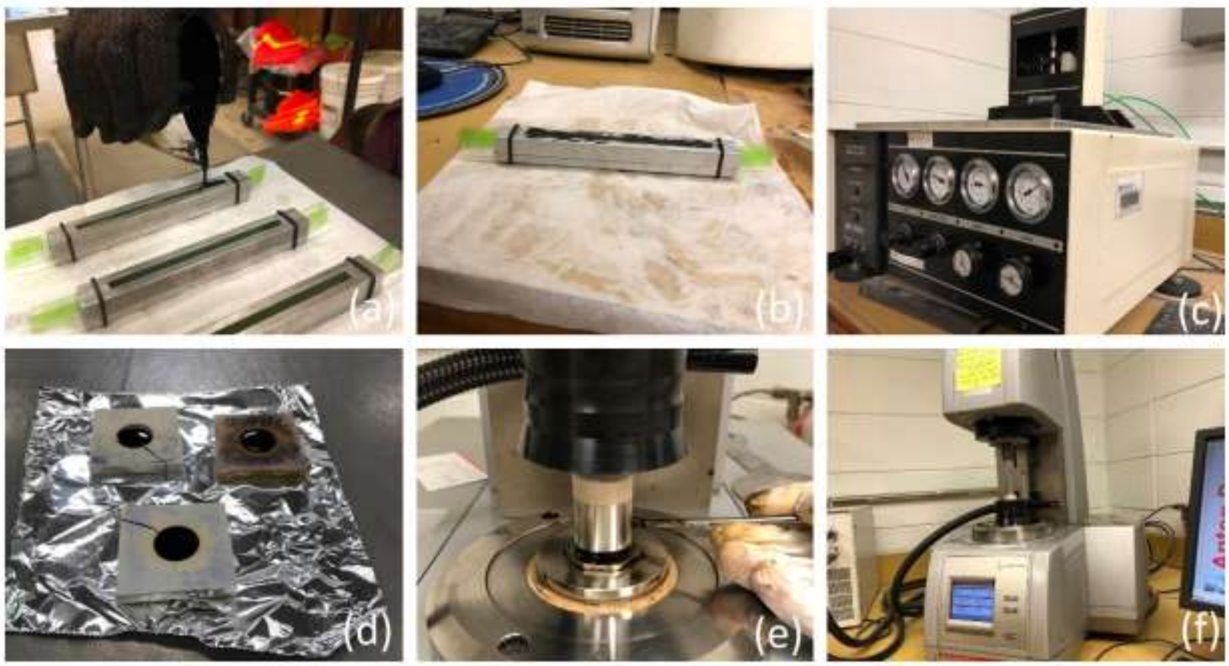


Figure 20
Sample preparation and PG testing: (a) pouring binder into the mold; (b) test mold taken out of the water bath prior to testing; (c) BBR; (d) filled silicone mold with binder; (e) trimming of the test specimen; and (f) ongoing test using DSR

Project Identification and Data Collection

Pavement segments that were constructed with crack sealing, chip seal, and microsurfacing were identified from the DOTD database. Since these maintenance treatments are usually applied on asphalt concrete overlays in Louisiana, AC overlay projects were also identified from the DOTD database to evaluate their field performance. This is an important step when evaluating the cost effectiveness of maintenance treatments. Video crack surveys were used in this study to locate the exact date and location of crack sealing, chip seal, microsurfacing, and AC overlays. Once these locations were identified, pavement performance data, Average Daily Traffic (ADT), type of the original pavement, layer thicknesses, and treatment costs were collected for these locations. These collected data were used to evaluate the field performance and cost effectiveness of crack sealing, chip seal, microsurfacing, and AC overlay.

Evaluation of the Field Performance of Crack Sealing

The objective of this task was twofold. First, the field performance of crack sealing was evaluated in flexible and composite pavements in Louisiana. Second, a regression model was developed to predict ΔPSL due to crack sealing knowing the original pavement type, surface conditions before treatment, and ADT. To achieve these objectives, the research team analyzed the sealed pavement sections to quantify the immediate benefits, in terms of performance jump, of crack sealing. Furthermore, the long-term performance of the crack-sealed sections was evaluated and compared with the untreated sections, in terms of the increase in PSL. The field performance of crack-sealed pavements was assessed in terms of random cracking and roughness data. Results of this task quantified the performance of crack sealing in extending the PSL.

Evaluation of the Field Performance of Chip Seal and Microsurfacing

This task aimed at evaluating the field performance of chip seals and microsurfacing applied on flexible pavements in Louisiana. To do so, the research team quantified the short and long-term benefits of these treatments on pavement conditions. This was accomplished through analyzing the collected PMS data and using a polynomial approach to model the pavement conditions as a function of time. Furthermore, the influence of different pavement factors on the performance of these treatments was evaluated. This helped in identifying the optimum timing for chip seal and microsurfacing applications.

Evaluation of the AC Overlays Service Lives

The objective of this task was to assess the PSL of structural AC overlays in Louisiana. This is an important step when evaluating the cost effectiveness of maintenance treatments because most of these treatments in Louisiana are applied on AC overlays. The research team evaluated the PSL of the selected AC overlay projects, in terms of PCI, RCI, RTI, and RFI.

Cost Benefits Analysis

A comprehensive cost benefits analysis was conducted for the use of crack sealing, chip seal, and microsurfacing when applied to AC overlays to evaluate the cost-effectiveness of these maintenance treatments and determine their optimal timing of application. To provide a thorough cost benefit analysis, this analysis was conducted considering single and multiple maintenance cycles

Cost Effectiveness of Maintenance Treatments for a Single Maintenance Cycle

The cost effectiveness of field crack sealing, chip seal, and microsurfacing projects was evaluated for a single maintenance cycle. To achieve this objective, the research team used collected data and calculated benefits from previous tasks to calculate the EAC, B/C, and CE for all the crack sealing, chip seal, and microsurfacing projects. The research team intended to use three economic indicators for each project to overcome the limitations of each indicator and to provide a more comprehensive analysis of cost-effectiveness.

Cost Effectiveness of Maintenance Treatments for Multiple Maintenance Cycles

The cost-effectiveness of maintenance treatments was evaluated for multiple maintenance cycles. This was achieved by considering a case study consisting of six alternative strategies over a 50-year analysis period. The six strategies consisted of successive AC overlays with different maintenance treatments (crack sealing, chip seal, and/or microsurfacing) applied in different orders as described in Figure 21 and Table 9. In each strategy, the maintenance treatment was applied when the overlay pavement condition (RCI in case of crack sealing or PCI in case of chip seal and microsurfacing) dropped to 75, 79, 82, or 87. This results in a total of 6*4=24 scenarios as shown in Table 10. The NPV was calculated for each scenario to determine the optimal strategy, along with the optimal timing of this strategy.

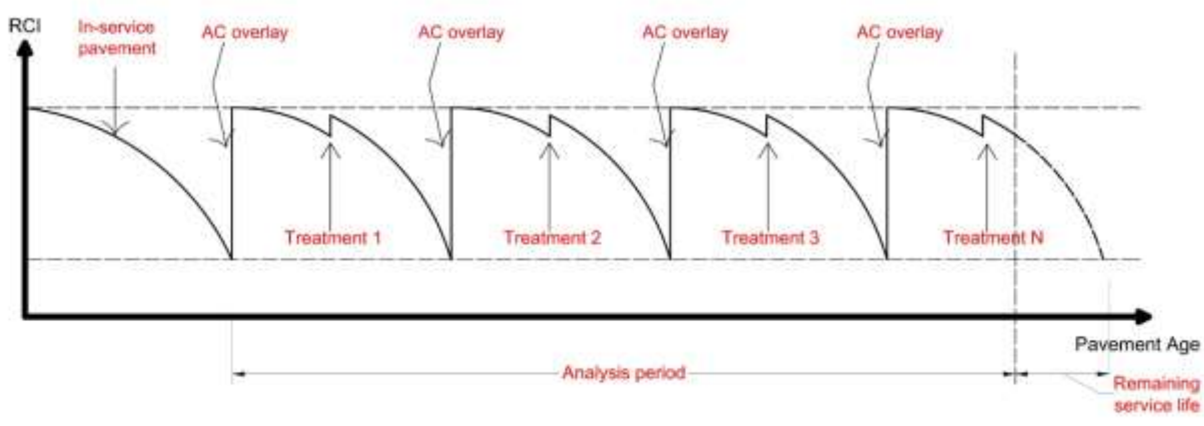


Figure 21
Illustration of the maintenance strategies

Table 9
Description of the six alternative strategies

Applied Maintenance Treatment	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5	Strategy 6
Treatment 1	None	Crack sealing	Chip seal	Microsurfacing	Chip seal	Microsurfacing
Treatment 2	None	Crack sealing	Chip seal	Microsurfacing	Microsurfacing	Chip seal
Treatment 3	None	Crack sealing	Chip seal	Microsurfacing	Microsurfacing	Chip seal
Treatment N	None	Crack sealing	Chip seal	Microsurfacing	Microsurfacing	Chip seal

Table 10
Different scenarios considered in the case study

Strategy / PCI- or RCI-	1	2	3	4	5	6
75	1 a	2 a	3 a	4 a	5 a	6 a
79	1 b	2 b	3 b	4 b	5 b	6 b
82	1 c	2 c	3 c	4 c	5 c	6 c
87	1 d	2 d	3 d	4 d	5 d	6 d

Experimental Program and Laboratory Testing

A field experiment was conducted in this research to evaluate the effect of crack sealing on moisture damage in AC. The LA 874 road section, which has a total length of two miles, was selected for the field experiment. This secondary road was constructed in Chase, Louisiana in 1940 and received 3.5 in. of AC overlay in 1999. This road section is subjected to low volume traffic (less than 200 vehicles per day). In the first cycle of testing prior to crack sealing, the following activities were conducted along the test section:

- **Distress survey**: the pavement surface showed numerous transverse and longitudinal cracks as shown in Figure 22(a).

- **Drainage survey**: two trapezoidal side ditches exist on both sides of the road with no subsurface drainage pipes. Figure 22(b) shows one of the side ditches.
- **Ground Penetrating Radar (GPR) survey:** a ground-coupled GPR having a center frequency of 900 MHz was used to scan the entire test section, see Figure 22(c).
- **Core extraction:** six cores were extracted for subsequent laboratory testing. The layer thicknesses were measured in accordance with ASTM D 3549. Figure 22(d) shows one of the extracted cores before laboratory testing.
- **Soil sampling:** samples from the base course and subgrade layer were extracted 14 days after the initial site visit and showed a loam subgrade beneath a cement-treated sandy loam base.

Crack sealing was applied to the last 0.5 mile of the section, leaving the first 1.5 miles untreated. Another site visit was made the following year along the entire section, and the aforementioned activities were repeated during the second visit. Furthermore, two tests were conducted in the laboratory to assist in the interpretation of the results, namely, the Lottman test (AASHTO T-283) and the falling head permeability test.

Figure 22
Illustration of main tasks conducted in the site visit

Lottman Test

In this study, the Lottman test was conducted in accordance with AASHTO T 283 to determine the soaking time after which stripping occurs in a conventional asphalt mixture having similar mix properties to the in-place mix on LA 874. Fifteen samples were prepared using the Superpave mix design procedure with an asphalt binder classified as PG 67-22. All samples were prepared using the same aggregate types, gradations, and binder content. In addition, all samples had a Nominal Maximum Aggregate Size (NMAS) of 0.5 in. (12.5 mm) and were compacted till reaching a final height of 3.7 in. (95 mm). The samples were then divided into five groups, namely, A, B, C, D, and E, each consisting of three specimens. Group A, the control group, was tested unconditioned. All other groups were conditioned by partial vacuum saturation with water then soaked in a water bath at 140 ^{o}F (Figure 23 a) as follows:

- Group B: was soaked in water for one day;
- Group C: was soaked in water for two days;
- Group D: was soaked in water for three days; and
- Group E: was soaked in water for four days.

An indirect tensile test, Figure 23 b, was then conducted on each sample of each group to determine the Tensile Strength Ratio (TSR) and its variation with soaking time.

(a) (b)

Figure 23
(a) Water soaking for the 12 samples and (b) split tensile test

Asphalt Saturated Hydraulic Conductivity

The falling head permeability test apparatus shown in Figure 24 was used to determine the saturated hydraulic conductivity (permeability), K_{sat}, of three asphalt cores extracted from the test section during the initial site visit. The test was conducted in accordance to Florida's test method FM 5-565 after soaking the asphalt cores in water for two hours.

Figure 24
Falling head permeability test

Evaluate the Effect of Crack Sealing on Moisture Damage

The objective of this task was to provide guidelines for using crack sealing to minimize moisture entrapment under the cracks; hereby, reducing stripping on low volume roadways. To achieve this objective, a calibrated Finite Element (FE) model was used to simulate the aforementioned field experiment. A sensitivity analysis was then conducted to compare between crack-sealed and unsealed sections under varying Ground Water Table (GWT) levels, air relative-humidity, air-temperatures, rain-intensities, and asphalt hydraulic conductivities.

Calibration of the Finite Element Model

Finite Element Analysis. To simulate the actual field conditions at log-mile 1.6, a steady-state analysis followed by two transient analyses (A and B) were conducted to model the pavement cross-section. The steady-state analysis was conducted to define the initial conditions of the system where a cracked cross-section was modeled starting from time zero. In the first transient analysis (A), the same cross-section was modeled starting from day zero until day 80 (corresponding to the crack sealing date). In the second transient analysis (B), a sealed cross-section was modeled starting from day 80 until day 308 (corresponding to the final site visit date). To differentiate between the cracked and sealed sections in the FE model, different crack geometries and boundary conditions were assigned, as described in the following sections. It is worth mentioning that all the analyses conducted in this study were coupled-analyses to adequately model the transient unsaturated flow of water, vapor, and heat through the pavement.

Material Properties. Thermal conductivity and volumetric heat capacity are required to simulate the heat flow through the pavement layers, while the Soil Water Characteristics Curve (SWCC) and hydraulic conductivity function are required to describe the unsaturated water flow through the pavement layers. Table 11 summarizes the material properties of the pavement layers as defined in the FE model. K_{sat} for the asphalt was measured in the laboratory while typical values from a previous study were assigned to the base and subgrade to account for the hydraulic conductivities of sandy loam and loam materials, respectively *[76]*. Since it is not cost-effective to directly measure suction values for AC, it is a common technique as suggested in previous studies to assume these values based on the material type and then to calibrate the results *[77, 78, 79]*. Therefore, Van Genuchten fitting parameters were selected from previous studies for the asphalt, base, and subgrade layers to account for the unsaturated flow through asphalt concrete, sandy loam, and loam materials, respectively *[76, 80]*. Similarly, typical thermal conductivities and heat capacities were assigned to the asphalt concrete, base, and subgrade to account for the thermal properties of asphalt concrete, sandy loam, and loam materials, respectively *[81, 82, 83]*.

Table 11
Material properties in the FE model

Property		Asphalt	Sandy loam base	Loam subgrade
Thermal conductivity (J/d/m/ºC)		125,150	57,813	44,870
Volumetric heat capacity (J/m³/°C)		1,881,580	1,500,000	1,500,000
Van Genuchten fitting parameters	Residual moisture content	0	0.065	0.078
	Saturated moisture content	0.0629	0.41	0.43
	n	1.0903	1.89	1.56
	a (kPa)	0.48937126	1.308	2.725
K_{sat} (m/sec)		$3.45x10^{-8}$	$1.22x10^{-5}$	$2.89x10^{-6}$

Finite Element Model Geometry. The general layout of the FE model is shown in Figure 25. The pavement cross section had a cross slope of 2.5% and a total width of 23.9 ft. (7.3 m). The pavement cross section consisted of a 4.5 in. (114.3 mm) asphalt concrete layer followed by a 9.5 in. (241.3 mm) base layer placed on top of the subgrade. The natural ground was extended laterally 36 ft. (11 m) beyond the side ditch on each side to be consistent with field conditions *[79]*. For this local road, the subgrade had the same properties as the natural existing soil. The side ditches had a bottom width of 1.5 m and a total depth of 0.9 m. Based on the distress survey, four longitudinal cracks were modeled as physical gaps in the pavement surface of the cracked section. These gaps had a width of 2.54 cm and a depth of 5.71 cm. In the sealed section, these gaps were closed forming impermeable regions.

Mesh Properties. The entire FEM included 3,973 quadrilateral and triangular elements. Fine mesh was assigned to the asphalt layer, specifically under the crack tips, to capture the moisture content (or saturation) gradients, while coarser mesh was assigned to the base and subgrade. The length of the smallest element was 2.0 cm based on a mesh sensitivity analysis.

Boundary Conditions. Boundary conditions assigned for the steady-state analysis were as follows, see Figure 25:

- Based on the drainage survey in the initial site visit, the water level in the left side ditch was about 0.8 m. This was simulated by a total hydraulic head (H) of 19.5 m along the wetted perimeter of the ditch [H= elevation of ditch bed (18.7 m) + pressure head (0.8 m) =19.5 m].
- Similarly, the water level in the right-side ditch was about 0.2 m, giving a total hydraulic head (H) of 18.9 m.
- A temperature of 74.5°F, obtained from the LSU Agricultural Center, was assigned in the model at 10 cm below the asphalt surface.
- To induce vertical and lateral drainage in the system, points of zero pressure head were applied at the bottom corners of the model (with H = 15.6 m).

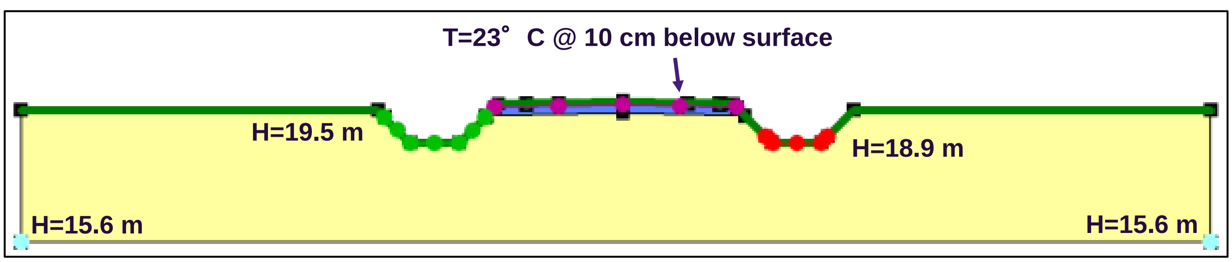


Figure 25
Model geometry and boundary conditions of the steady-state analysis

The boundary conditions assigned for the transient analyses were as follows, see Figure 26:

- Similar drainage conditions were assigned at the bottom corners of the model, as previously mentioned.
- Time-dependent temperature, shown in Figure 27 (a), was assigned at 10 cm below the pavement surface.
- Boundary condition for the Land Climate Interaction (LCI) was assigned along the asphalt concrete surface and crack tips. In the sealed cross-section, this condition was removed from the crack tips. The LCI boundary condition is specifically formulated to allow for coupling of the climatic conditions to the ground surface, see Figure 27 (b, c, d, e, and f). This boundary condition is required to compute the surface evaporation based on the actual Volumetric Moisture Content (VMC) in the ground using the Penman-Wilson procedure *[84]*.

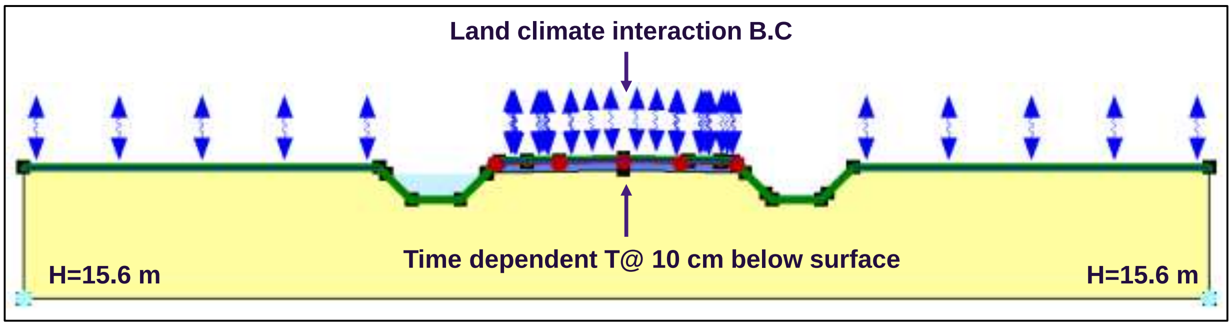


Figure 26

Boundary conditions of the transient analyses

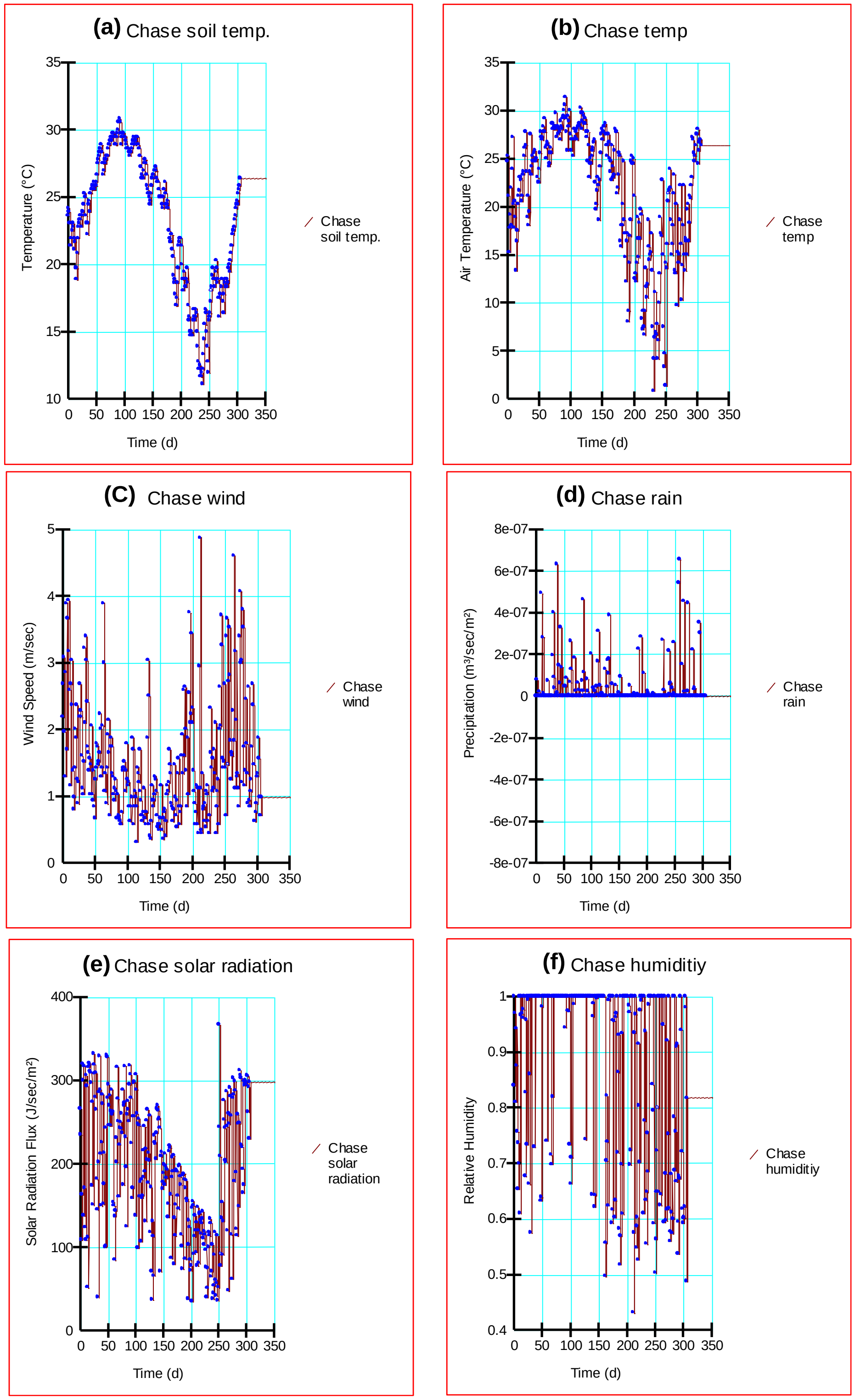


Figure 27

Soil temperature and climatic conditions for Chase district for the 308 days analysis period

Sensitivity Analysis

The calibrated finite element model was used to develop two parametric models, namely, sealed and unsealed finite element models. Each model had its relevant crack geometry and boundary conditions as previously discussed. For each model, an hourly transient analysis was conducted considering four hours of rainfall followed by a dry period of 68 hours. This resulted in a total transient analysis period of 72 hours or three days. Multiple runs were conducted simulating a wide range of asphalt permeabilities, rain intensities, groundwater table (GWT) depths, air temperatures, and relative humidity in order to develop a framework that can be used for different asphalt mixes and in different climatic regions.

Evaluate the Effect of Chip seal and Microsurfacing on Moisture Damage

The objective of this task was to assess whether chip seal and microsurfacing significantly contribute to moisture damage. To do so, 1,524 core reports obtained from DOTD throughout the nine districts in Louisiana, were analyzed. Out of these cores, 1,156 cores (76%) were extracted from untreated AC pavement sections, 311 cores (20%) were extracted from chip sealed AC pavement sections, and 57 cores (4%) were extracted from AC pavement sections treated with microsurfacing. The research team visually inspected all of the 1,524 cores to identify the stripped cores. After that, all the cores were categorized based on the district number, treatment type (chip-seal, microsurfacing, or untreated), and stripping conditions (stripped or non-stripped). Results of this analysis evaluated whether chip seal and microsurfacing significantly contribute to moisture damage. Furthermore, a detailed forensic analysis was conducted to six and four moisture-damaged sections with chip seal and microsurfacing, respectively, to evaluate the contributing factors to this failure.

Develop an Enhanced Decision Making Tool

Since pavements vary in their behavior and potential needs depending on type of pavement structure, groundwater table level, age, climate, traffic, and other factors; the success of crack sealing and other surface treatments was not expected to be the same for all encountered conditions. Instead, the benefits and cost-effectiveness of such treatments are more significant for specific road conditions. Therefore, the objective of this task was to include the results of the previous tasks into an enhanced decision-making tool that selects the best maintenance treatment (crack sealing, chip seal or microsurfacing) to be used on an existing AC overlay based on the specific road conditions. In the selection process, the following three key criteria were considered:

1. Surface distresses in the existing overlay, such as, surface cracks, rutting, and roughness;

2. Potential subsurface moisture damage as a result of maintenance treatment application; and
3. Cost effectiveness of the applied maintenance treatment.

Furthermore, the developed tool allows one to determine the optimal timing, in terms of RCI or PCI, for the recommended maintenance treatment. In order to ensure that the developed tool is time-efficient and simple to use, the tool was developed using macros in Microsoft Excel.

DISCUSSION OF RESULTS

Review of DOTD State-of-the-Practice

A statewide comprehensive survey was conducted to gather information from districts and cities in Louisiana as related to the current practices in using crack sealants and other impermeable surface treatments and their effectiveness as a preventive maintenance activity. Figure 28 shows the districts that responded to the survey. In total, six out of the nine districts responded to the survey: Districts 4, 5, 7, 8, 58, and 61. A copy of the survey is provided in Appendix A.

Figure 28
Districts' response to the survey

The research team contacted practitioners in the districts to gage opinions and experiences that have not been formally published on this topic and to understand the decision processes, which are used to determine when crack sealing and other impermeable surface treatments are selected. To expedite the response to the survey, the survey questionnaire focused on seven main questions as follows:

1. Which of the pavement preservation methods do you currently use in your district/city/parish (Highlight all methods that you use)?

2. Do you keep record of the roads (construction files) in which the different treatment methods are used?
3. What is the overall budget spent in 2014, 2015, or 2016 on the different treatment methods?
4. Do you select the roads to be treated based on pavement conditions (PMS data) through a pre-set schedule, or visual inspection?
5. Do you construct the different treatment methods in-house or through external contracts?
6. Do you perform any laboratory testing for acceptance of crack sealant materials?
7. Do you perform any Quality Assurance (QA) for acceptance of the installed treatment methods?

Common Pavement Preservation Methods in Louisiana

Respondents were queried on the currently used pavement preservation methods in their districts and whether they keep records (construction files) of the treated roads. As shown in Figure 29, chip seal followed by crack sealing are the two most common preventive maintenance treatments used in Louisiana. All the six districts use chip seal while crack sealing is employed in four out of the six districts. On the other hand, ultrathin overlay and microsurfacing are used in three districts, while ultrathin bonded wearing course is only used in two districts. It is interesting to note that neither fog seal nor slurry seal are used in any of the six districts. As shown in Figure 29, most of the districts keep records of their treated roads.

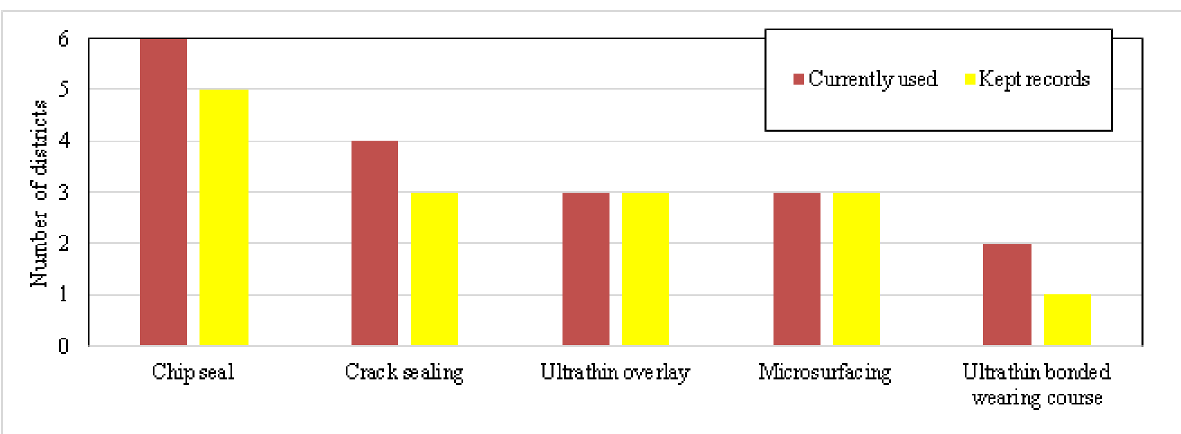


Figure 29
Preventive maintenance treatments used in districts of Louisiana

Annual Budget for Different Treatment Methods

Respondents were queried on the overall budget spent in 2014, 2015, or 2016 on the different treatment methods. None of the respondents provided any financial data related to ultrathin overlay, ultrathin bonded wearing course, fog seal, or slurry seal. Table 12 presents the annual budget spent by each district on crack sealing, chip seal, and microsurfacing. As expected, chip seal received the highest average annual budget because it is used in all the districts. Although crack sealing is commonly used in most of the districts, it is allocated the lowest average annual budget due to its relatively low cost.

Table 12
Annual budget spent on different treatment methods ($)

Treatment	District						Average annual budget
	4	5	7	8	58	61	
Crack sealing	211,000	-	-	30,000	30,000	-	90,333
Chip seal	3,100,000	-	500,000	-	1,500,000	-	1,700,000
Microsurfacing	-	-	380,000	1,063,000	1,700,000	-	1,047,667

Criteria for the Selection of Treated Roads

Figure 30 presents the criteria used by districts to select the roads to be treated, namely, (1) based on pavement conditions (PMS data) only, (2) based on visual inspection only, and (3) based on both. As shown, 75% of the districts that use crack sealing apply this treatment based on visual inspection only, while 25% apply it based on both, visual inspection, and PMS data. On the other hand, all the other treatment methods are applied in all the districts based on the PMS data and visual inspection.

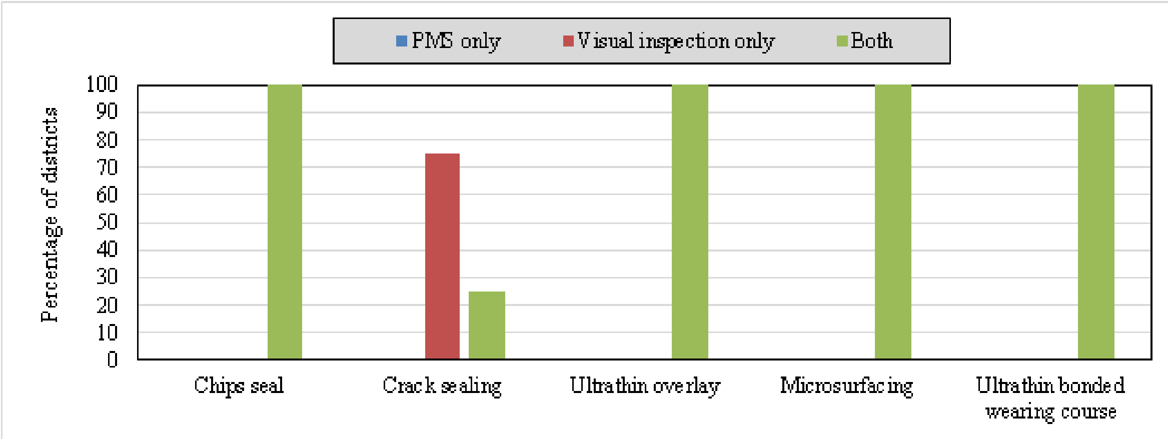


Figure 30
Criteria to select the roads to be treated

Construction of Treatment Methods

Districts were queried on the method they use to construct the different maintenance treatments, namely, (1) in-house application, (2) through external contracts, or (3) through both. Figure 31 presents the methods used for each maintenance treatment. As shown in this figure, microsurfacing and ultrathin bonded wearing course are performed through external contracts only possibly due to the high degree of labor coordination and experience required. Similarly, all the districts perform chip seal through external contracts; however, one district uses both in-house and external contracts. Conversely, all the districts that use crack sealing perform in-house application. This is possibly because crack sealing can be constructed more efficiently with in-house crews. It is worth noting that one district that frequently uses crack sealing uses both in-house and external contracts. The results of the survey also indicated that districts that use ultrathin overlays use both in-house and external contracts.

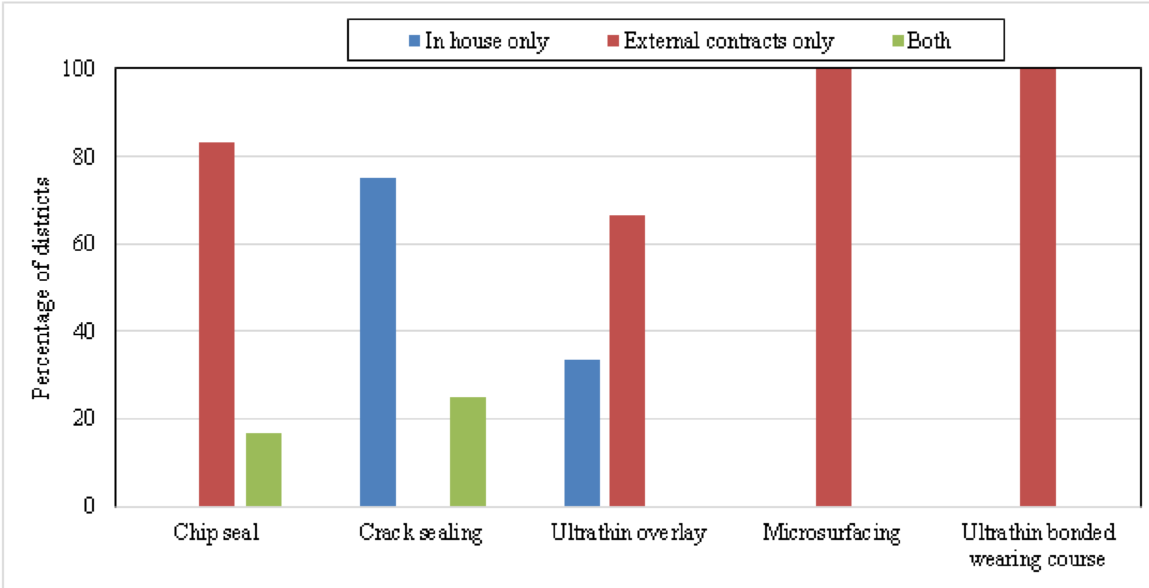


Figure 31
Construction of different maintenance treatment methods

Laboratory Acceptance Tests of Crack Sealant Materials

The four districts that currently use crack sealing were queried whether they perform any laboratory testing for acceptance of crack sealant materials. Three out of the four districts indicated that they perform laboratory testing prior to purchasing the sealant material to ensure that it passes their construction material specifications.

Quality Assurance of Installed Treatment Methods

Figure 32 presents the percentage of districts that perform Quality Assurance (QA) activities for the installed treatment methods. As shown in Figure 32, all the districts that use chip seal, microsurfacing, or ultrathin bonded wearing course perform quality assurance after installation. Out of the total districts that use ultrathin overlay, about 67% (two-thirds) perform quality assurance after installation. Almost all the districts performing quality assurance for installed surface treatments indicated that the quality assurance is conducted in accordance to DOTD Item 507 specifications. On the other hand, only 50% of the districts that use crack sealing perform quality assurance in the form of visual inspection.

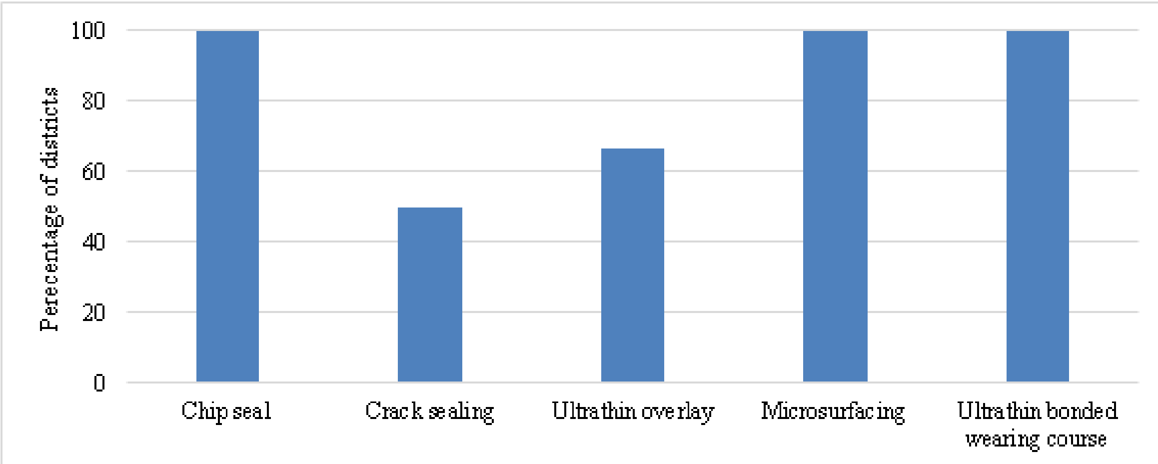


Figure 32
Percentage of districts performing Quality Assurance for different installed treatment methods

Laboratory Evaluation of Crack Sealant Materials

ASTM D 6690-15 Test Results of Rubberized Asphalt

Cone Penetration Test. The cone penetration test was conducted in accordance with ASTM D 5329 – 16, *Standard Test Methods for Sealants and Fillers, Hot-Applied, for Joints and Cracks in Asphalt Pavements and Portland Cement Concrete Pavements*. The three penetration values in 0.1 mm units were 71, 80, and 81. Therefore, the sample penetration, which is the average of the three readings, was measured at 77. This value conforms to the specifications, which specify the sample penetration to be less than 90 for Type II materials.

Resilience Test. The resilience test was conducted in accordance with ASTM D 5329 – 16, *Standard Test Methods for Sealants and Fillers, Hot-Applied, for Joints and Cracks in Asphalt Pavements and Portland Cement Concrete Pavements*. The results of the three measurements are presented in Table 13. Based on these results, the sample resilience, which is the average recovery of the three readings, was calculated at 67%. This value conforms to the specifications, which specify the resilience to be greater than 60% for Type II materials.

Table 13
Results of the resilience test

Trial	Penetration (P) in 0.1 mm	Final Dial reading (F) in 0.1 mm	Recovery (%)= P+100-F
1	5	42	63
2	15	36	79
3	10	50	60

Softening Point Test. The softening point test was conducted in accordance with ASTM D 36/D 36M −14, *Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus).* The measured softening point for the tested sample was 94ºC, which is greater than the minimum specified value for Type II materials (80ºC).

Bond Test. The bond test was conducted in accordance with ASTM D 5329 – 16, *Standard Test Methods for Sealants and Fillers, Hot-Applied, for Joints and Cracks in Asphalt Pavements and Portland Cement Concrete Pavements.* As specified for Type II materials, the three tested specimens passed three cycles of 50% extension at -29°C.

PG Test Results of Rubberized Asphalt and Asphalt Emulsion

The rheological test results of the emulsified crack sealant residue and rubberized asphalt binder are presented in Table 14 and Table 15, respectively. As shown in these tables, the high temperature grade for the emulsified crack sealant residue and the rubberized asphalt binder was PG 58 and PG 88, respectively. The low temperature grade for the emulsion residue was PG -28. However, the low temperature grade for the rubberized asphalt binder could not be determined since the sample was too soft and therefore, could not be tested using the BBR.

Table 14
Rheological test results for asphalt emulsion (CRS-2) residue

Equipment Test and AASHTO Method	Specification	Test Temperature (°C)	Crack Sealant Emulsion
Original Residual Emulsion			
Dynamic Shear, 10 rad/s, G*/Sin(δ), KPa AASHTO T 315	1.00+	58	1.47
		64	0.781
Rolling Thin-Film Oven Residue			
Dynamic Shear, 10 rad/s, G*/Sin(δ), KPa AASHTO T 315	2.20+	58°C	2.89
		64°C	1.43
Pressure Aging Vessel Residue,100°C			
Dynamic Shear, 10 rad/s, G*/Sin(δ), KPa AASHTO T 315	5000-	13°C	7041
		16°C	4940
Bending Beam Creep Stiffness, S, (MPa) 60s AASHTO T313	300-	-18	250
		-24	468
Bending Beam Creep Stiffness, m-value, 60s AASHTO T313	0.300+	-18	0.307
		-24	0.261
PG Grading			58-28

Table 15
Rheological test results of rubberized asphalt binder (Crafco)

Equipment Test and AASHTO Method	Specification	Test Temperature (°C)	Crack Sealant Binder
Original Binder			
Dynamic Shear, 10 rad/s, G*/Sin(δ), KPa AASHTO T 315	1.00+	100°C	1.092
		106°C	0.667
Rolling Thin-Film Oven Residue			
Dynamic Shear, 10 rad/s, G*/Sin(δ), KPa AASHTO T 315	2.20+	88°C	3.48
		94°C	2.13
Pressure Aging Vessel Residue,100°C			
Dynamic Shear, 10 rad/s, G*/Sin(δ), KPa AASHTO T 315	5000-	1°C	3410
		-2°C	3910
		-5°C	N/A
Bending Beam Creep Stiffness, S, (MPa) 60s AASHTO T313	300-	-18	Material was too soft to be tested using the BBR.
		-24	
Bending Beam Creep Stiffness, m-value, 60s AASHTO T313	0.300+	-18	
		-24	
PG Grading			88-

Project Identification and Data Collection

DOTD databases were mined for preliminary identification of the crack sealing, chip seal, microsurfacing, and AC overlay projects. Unfortunately, these databases only identified the treated section and not the exact location or extent of the treatment activities on that section. Therefore, for the entire length of these projects, videos between 2003 and 2015 were reviewed to determine the exact date and location of crack sealing, chip seal, microsurfacing, and AC overlay; see examples in Figures 33 to 36. It is worth noting that unsealed data points (log-miles) were selected before and/or after the selected crack-sealed data points for comparative evaluation.

To provide an accurate representation of the effect of the applied maintenance treatments, the analysis was conducted for every log-mile, which was considered as a single data point. On the other hand, a single average value was calculated for AC overlays over the project limits for each collection year and was considered as a single data point in the analysis.

Figure 33
Pavement section before (left) and after (right) crack sealing

Figure 34
Pavement section before (left) and after (right) chip seal

Figure 35
Pavement section before (left) and after (right) microsurfacing

Figure 36
Pavement section before (left) and after (right) AC overlay

Once the data points were identified for each treatment type, ADT, type of pavement, layer thicknesses, treatment costs, and performance data were collected for these points. Specifically, RCI and RFI were obtained for the crack-sealed data points. Similarly, PCI, RTI, and RFI were obtained for the data points treated with microsurfacing, chip seal, and AC overlays. For any data point to be included in the analysis, it had to meet the following acceptance criteria:

- Has at least one index value before treatment application;
- Has at least three index values after the treatment application; and
- Exhibit negative slope in distress development over the treatment service life.

Figure 37 presents the location of the treated control sections selected in this study, while Tables 16 and 17 summarize the total number of data points considered in the analysis for crack sealing, chip seal, and microsurfacing.

Table 16
Size and description of data sets used in the analysis of crack sealing

Index	Data Set ID	Sealed segment	Unsealed segment	Type of analysis
RCI	1	306 (28)[1]	-	PJ for sealed log miles
RCI	2	38 (18)	38 (18)	APG between sealed and unsealed log miles
RCI	3	248 (20)	125 (20)	PSL* between sealed and unsealed segments
RCI	4	143	-	ΔPSL of sealed log miles.
RCI	5	32	-	Comparison between ΔPSL of sealed log miles under different traffic levels
RFI	6	306 (28)	-	PJ for sealed log miles
RCI	7	190	-	Cost benefit analysis of crack sealing projects

[1] Log miles (control sections)

Table 17
Summary of the control sections and data points used in the analysis of chip seal, microsurfacing, and AC overlay.

Index	Chip seal			Microsurfacing			AC overlay		
	Data Set	Control sections	Log miles	Data Set	Control sections	Log miles	Data Set	Control sections	Data points
PCI	8	47	316	9	25	322	10	141	141
RCI		39	379		-	-		141	141
RFI		42	334		27	360		141	141
RTI		-	-		27	324		141	141

Figure 37
Location of the treated control sections selected in this study

Evaluation of the Field Performance of Crack Sealing

To quantify the benefits of crack sealing, the PJ, APG, PSL*, and ΔPSL were computed and analyzed. In this research, the term RCI^- refers to the last RCI collected before sealing date (pre-treatment random cracking index), this also applies to all the other indices. Furthermore, ΔRCI refers to the difference between RCI at sealed and unsealed log miles (sealed - unsealed) at time (i).

Performance Jump (PJ)

The Performance Jump (PJ) for RCI and RFI was calculated using Data Sets 1 and 6, respectively; see Table 16. For the RCI, all the 306 log miles showed positive values with mean values of 7.4 ± 7.3, which indicates that crack sealing had a significant immediate impact on RCI as shown in Figure 38. On the other hand, for the RFI, only 22% of the 306 log miles had a positive PJ with mean values of 2.3 ± 2. This indicates that crack sealing had minor or negligible immediate impact on surface roughness as suggested by other studies *[32, 33]*. Therefore, the analysis of the long-term field performance of crack sealing in the following sections was limited to RCI.

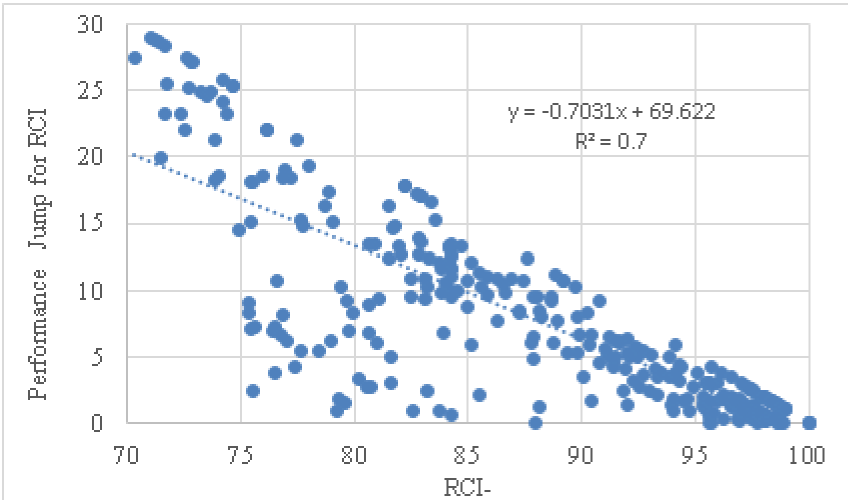


Figure 38
Correlation between PJ and RCI⁻

Average Performance Gain (APG)

Data Set 2 in Table 16 was used to calculate the APG. Figure 39 presents the APG for each pair of sealed and unsealed log miles and the corresponding RCI^-. The results indicated that all pairs had positive APG supporting that crack sealing improved pavement performance against random cracking. No strong correlation was observed between the APG and RCI^- as indicated by the coefficient of determination (R^2), which had a value of 0.24. Yet, within the evaluated range, the general trend suggests that higher performance gains were achieved with lower values of RCI^-.

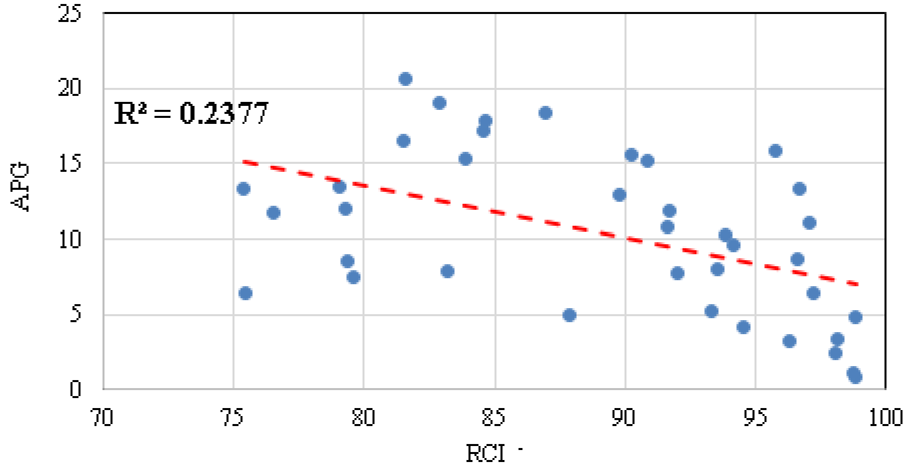


Figure 39
Correlation between APG and RCI-

Increase in Pavement Service Life (PSL*)

Data Set 3 in Table 16 was used to evaluate the effects of crack sealing in extending pavement service life when compared with the untreated segments by calculating PSL*. As a first step, the research team selected a threshold for RCI for PSL calculations. Based on local surveys, it was reported that Louisiana districts use visual inspection instead of PMS data to select candidate sections for crack sealing. Therefore, a threshold for RCI of 69 was assumed to match the pavement-rating scheme used by DOTD for other cracking distresses *[69]*. Second, the PSL for sealed and unsealed log-miles was calculated and grouped by control section, and the average PSL was calculated for both segments (sealed and unsealed). The average PSL of unsealed segment was then subtracted from that of the sealed segment to obtain PSL*.

Figure 40 presents PSL* and ΔRCI before sealing (ΔRCI^-) for each control section. For most of the sections, the sealed segment showed an average PSL* of two years more than the unsealed segment, which is comparable with other studies *[5]*. Statistical t-tests were conducted to compare the average PSL of sealed and unsealed segments for the 17 sections that experienced positive PSL*. The results indicated that this increase was significant for all the control sections except for sections 8, 10, 15, 20, and 25. It is noted that sections 12 and 13 experienced negative PSL* because the unsealed segment in these sections had an average RCI^- of 100. Furthermore, section 24 had severe fatigue cracks, which cannot be treated by crack sealing; therefore, no positive PSL* was calculated for this section *[85]*.

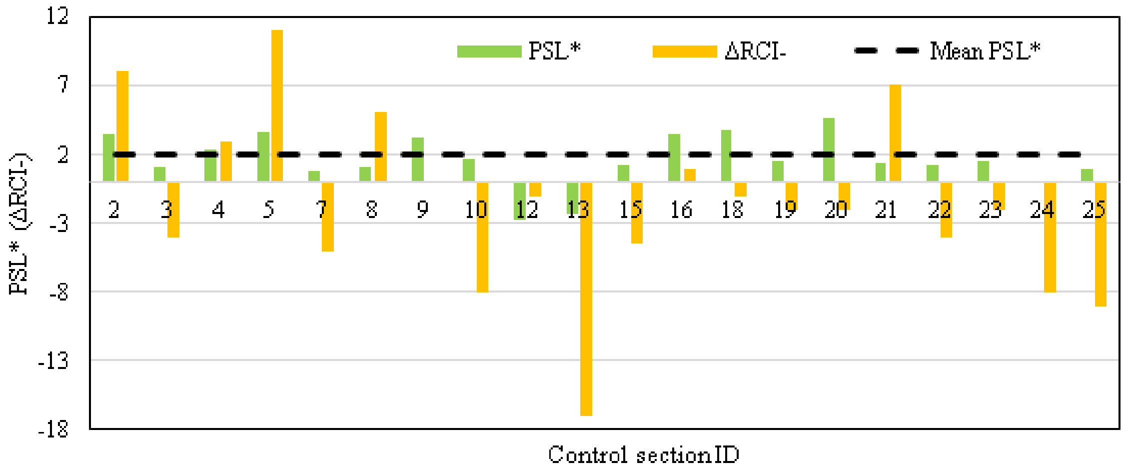


Figure 40
PSL* and ΔRCI$^-$ for different control sections

Increase in Pavement Service Life (ΔPSL)

Any differences between sealed and unsealed segments, in terms of pavement structure, pre-treatment pavement conditions, or traffic would affect the accuracy of PSL*. Therefore, these differences were eliminated by calculating the increase in PSL for each sealed log mile when compared with the original pavement using Data Set 4 in Table 16. In this analysis, RCI performance curves were plotted before and after crack sealing and ΔPSL was calculated using equations (12), (13), and (14). Figure 41 illustrates ΔPSL and RCI$^-$ for Data Set 4 for both pavement types. Negative values of ΔPSL indicate that no extension in the pavement service life was achieved after crack sealing, and therefore, the extension in the PSL was set to zero.

As shown in Figure 41, both pavement types followed similar trends such that ΔPSL had negative values for RCI$^-$ more than 90. As an example, Figure 42 shows the RCI before and after crack sealing for one of the points that exhibited negative PSL where crack sealing was applied in 2010. As shown, the application of crack sealing did not reduce the rate of pavement deterioration.

When RCI$^-$ was less than 90, crack sealing extended PSL by an average of 5.6 ± 1.9 and 3.15 ± 1.3 years for flexible and composite pavements, respectively. This suggests that no extension in PSL would be achieved when sealing pavements in very good conditions (RCI$^-$ >90). This is due to the fact that when crack sealing is applied too soon, it adds little benefits to the original overlay since nearly all the remaining performance of the original overlay is still unused.

No clear trend was observed when ΔPSL was plotted against ADT for Data Set 4, possibly because the sections had different initial RCI^-. Therefore, the evaluation of traffic volume on ΔPSL was limited to points having exactly the same RCI^-, which are included in Data Set 5 in Table 16. Figure 43 presents ΔPSL versus RCI^- for different traffic levels. The results indicated that the benefits of crack sealing, in terms of ΔPSL, were greater for lower ADT, which agrees with previous studies *[28]*.

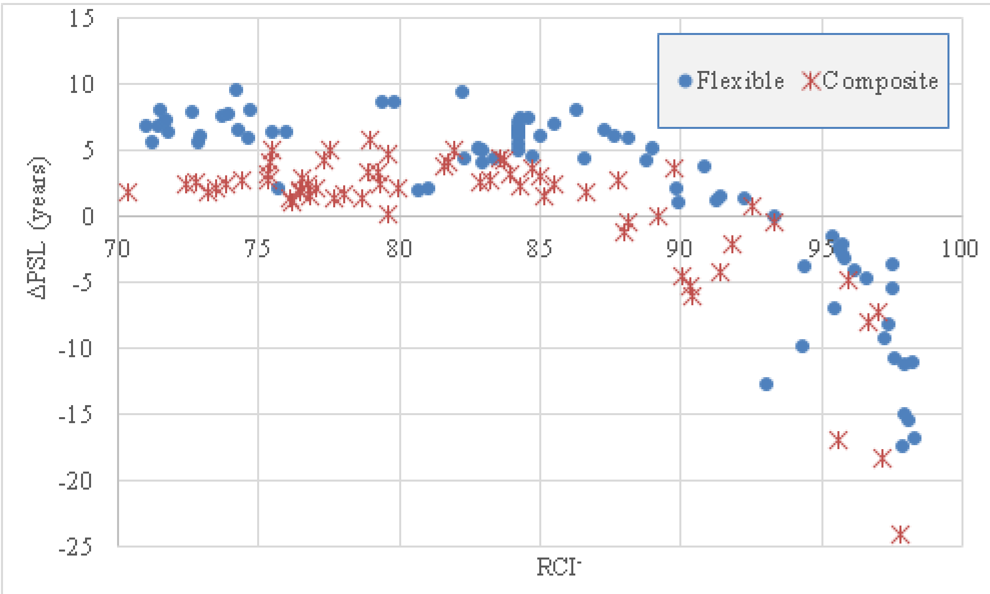


Figure 41
ΔPSL versus RCI^- for Data Set 4

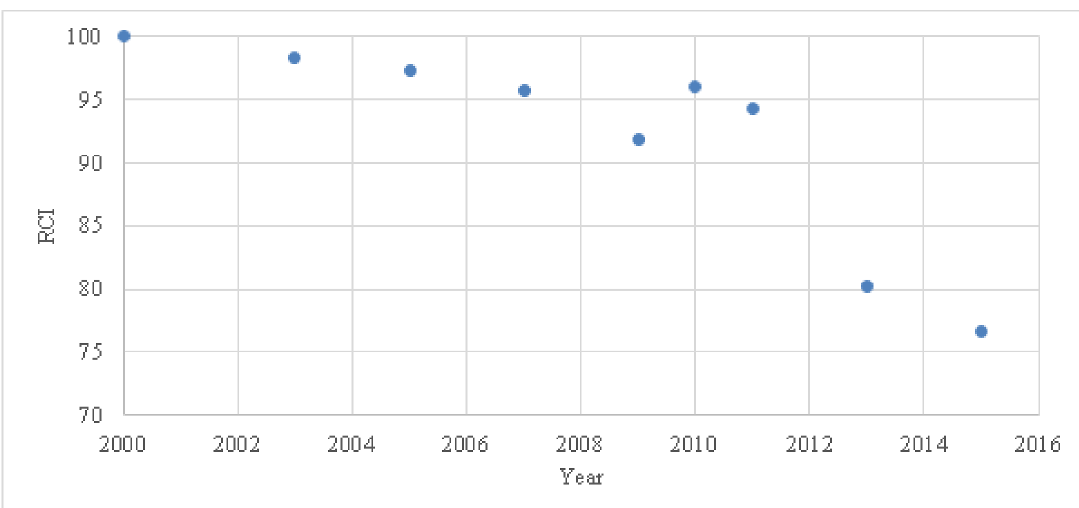


Figure 42
RCI before and after crack sealing for control section 01-03 at log-mile 3.6

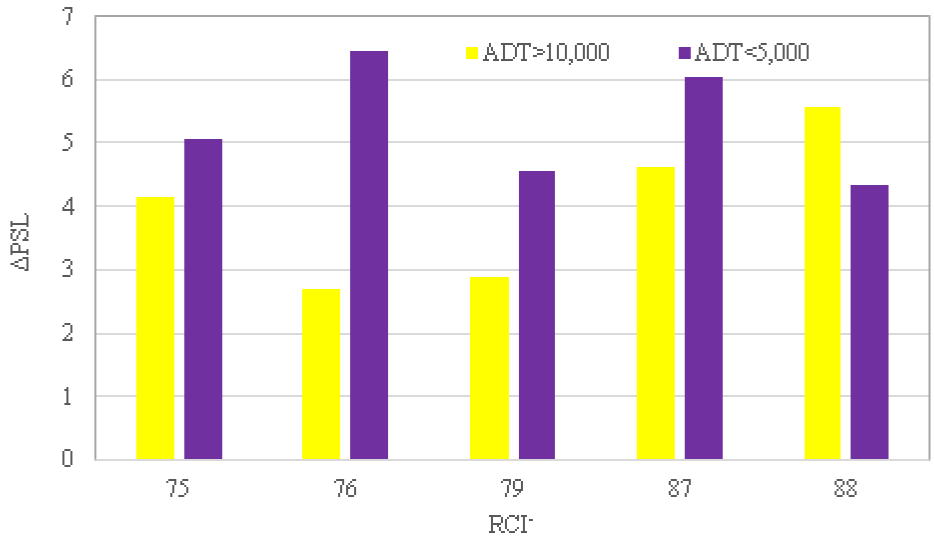


Figure 43
ΔPSL versus RCI$^-$ for different traffic levels

Model Development

Based on a review of past studies, four primary variables were considered in the regression analysis: pavement type, pavement age at sealing date, RCI$^-$, and ADT. An Analysis of Variance (ANOVA) was conducted between ΔPSL and these four variables using SAS 9.4 software, see Table 18. RCI$^-$ had the highest statistical correlation to ΔPSL (lowest P-value), followed by pavement type and ADT, while pavement age at sealing date was not statistically correlated to ΔPSL. Therefore, only RCI$^-$, ADT, and pavement type were considered in the regression model.

Table 18
Results of Analysis of Variance

Variables	**t-value**	**P-value**	**Interpretation**
Intercept	7.36	< 0.001	Significant
RCI$^-$	-9.56	< 0.001	Significant
Pavement age at sealing date	0.23	0.82	Not Significant
ADT	4.39	< 0.001	Significant
pavement type	-5.47	< 0.001	Significant

For each pavement type, 70% of the data was used to fit the model and 30% was used for validation. This resulted in 80 points for flexible pavements (56 for fitting and 24 for validation), and 63 points for composite pavements (44 for fitting and 19 for validation). The fitted models developed after performing non-linear regression analyses on the ΔPSL as a dependent variable, and with RCI^-, and ADT as the independent variables were as follows:

Flexible Pavement

$$\Delta PSL = (-77.4535608061868 * RCI^-) + (0.97237502931102 * \{RCI^-\}^2) + (-0.00405474148271548 * \{RCI^-\}^3) + (-0.000274483979066505 * ADT) + (-1.75051070532218 E^{-07} * ADT^2) + (1.56602824484588 E^{-11} * ADT^3) + 2057.89818151366 \quad (23)$$

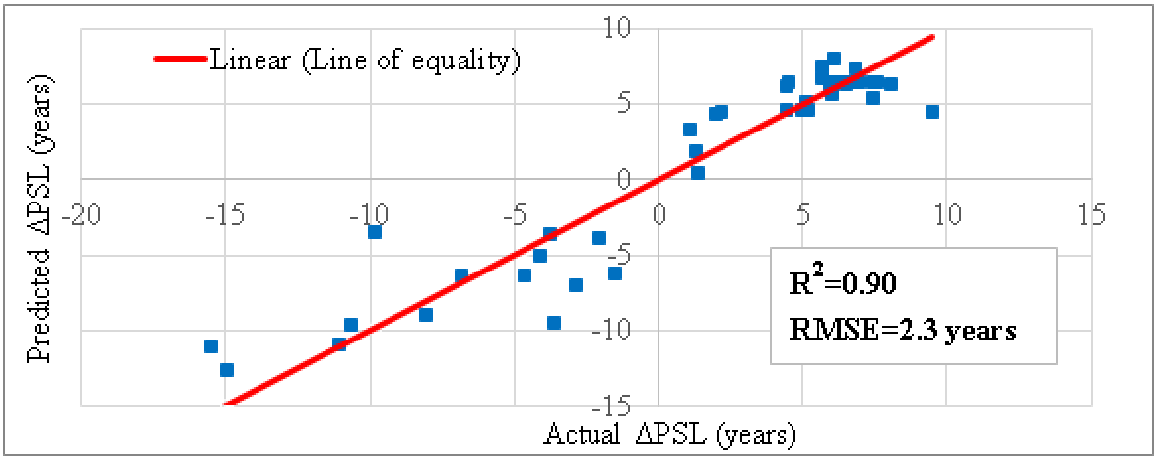
where ADT<=11,100, and 70 <RCI^- <100

Composite Pavement

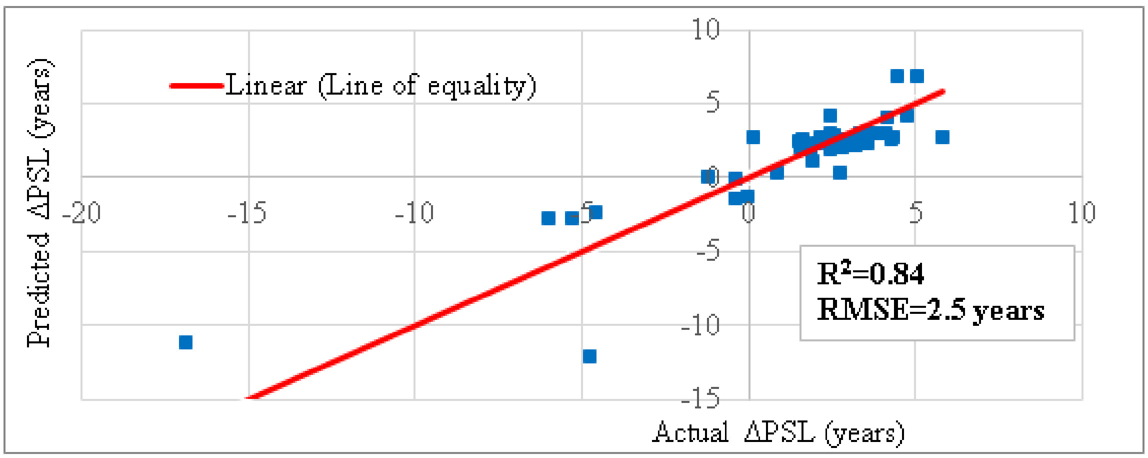
$$\Delta PSL = (-45.780008257557 * RCI^-) + (0.602560966823236 * \{RCI^-\}^2) + -0.00263494541718199 * \{RCI^-\}^3) + (0.000434768438768629 * ADT) + (1.39083191633572E^{-07} * ADT^2) + (-1.09975897301029E^{-11} ADT^3) + 1157.69616030286 \quad (24)$$

where ADT<=15,100, and 70 <RCI^- <100

Figure 44 (a and b) presents the actual and predicted ΔPSL using fitting data for both pavement types. For both types, it is clear that the proposed models predicted ΔPSL with an acceptable level of accuracy as supported by the R^2 and the root mean square error (RMSE) shown in the figures. For flexible pavements, the R^2 and RMSE were 0.9 and 2.3 years, respectively, while for the composite pavement, the R^2 and RMSE were 0.84 and 2.5 years, respectively. The proposed model for flexible pavements was plotted for different RCI^- and ADT; see Figure 45. It is noted that the developed model follows the same trends shown in Figures 41 and 43 based on the measured data.



(a)



(b)

Figure 44
Predicted ΔPSL versus actual ΔPSL using fitting data for (a) flexible pavements and (b) composite pavements

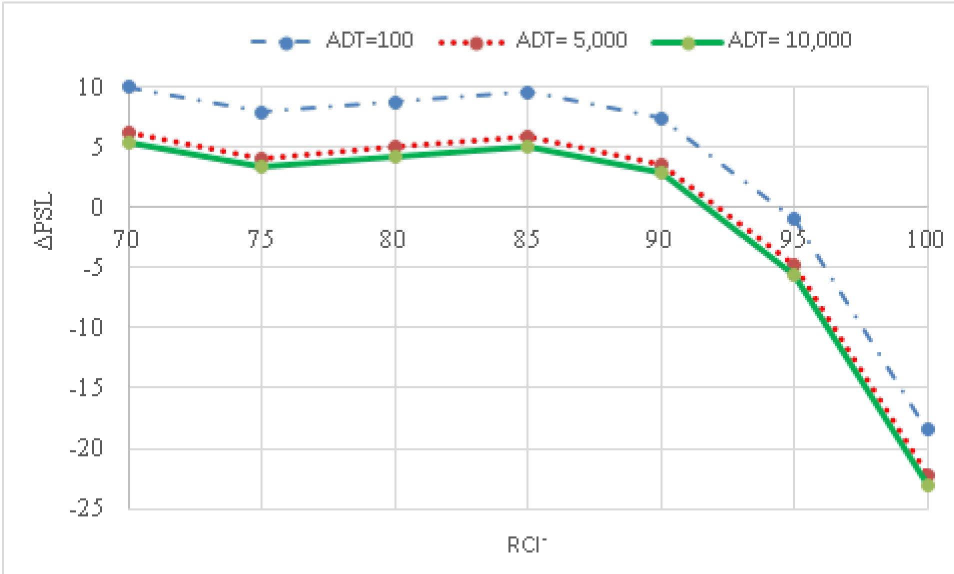


Figure 45
Predicted ΔPSL versus RCI^- for flexible pavements under different ADT

Illustrative Applications of the Predictive Model

During the planning of maintenance activities, a contractor and/or state agency may be interested in determining whether crack sealing is an appropriate treatment at the site. The proposed model is expected to help in this process by providing two main functions:

1. **Deciding whether crack sealing should be applied:** Negative values of predicted ΔPSL mean that crack sealing would provide no additional benefits and thus is not recommended.
2. **Select the optimal timing for future treatments:** following crack sealing through accurate predictions of positive values of ΔPSL.

Tables 19 and 20 present the application of the developed models in estimating ΔPSL using validation data. It is noted that these data points were not used in the model development, and thus would reflect the model accuracy. As shown in Tables 19 and 20, the developed models successfully satisfied the first function, since all the actual values were predicted with the correct sign (positive or negative). Furthermore, the models for flexible and composite pavements were efficient in predicting the magnitude of positive values of ΔPSL, with RMSE of 1.1 years.

Table 19
Illustrative application of the proposed model for flexible pavements

RCI⁻	ADT	Actual ΔPSL	Predicted ΔPSL	RMSE (Years)
88.77	3000	4.34	6.43	1.1
72.93	2600	6.06	6.61	
79.77	2600	8.72	7.10	
82.27	6500	4.43	4.48	
84.22	11100	4.99	6.43	
84.19	11100	5.53	6.43	
84.23	11100	7.14	6.43	
87.25	11100	6.5	6.00	
91.42	5500	1.61	1.59	
89.84	5500	2.169	3.36	
79.4	3000	8.73	6.65	
71.77	2600	6.43	7.11	
71.66	2600	7.18	7.17	
71.01	2600	6.9	7.57	
74.24	2600	6.56	6.33	
74.66	2600	8.01	6.29	
72.62	2600	7.86	6.72	
73.89	2600	7.8	6.38	
95.60	5500.00	-2.38	-6.70	5.4
98.25	3700.00	-10.99	-13.71	
97.26	1870.00	-9.25	-8.56	
93.00	6000.00	-12.70	-1.24	
93.33	5500	-0.03	-1.48	
95.84	5500	-3.19	-7.36	

Table 20
Illustrative application of the proposed model for composite pavements

RCI^-	ADT	Actual ΔPSL	Predicted ΔPSL	RMSE (Years)
81.94	15100	4.988	2.95	1.1
83.22	15100	2.71	2.73	
84.27	15100	2.23	2.42	
84.68	2300	3.59	3.45	
75.44	320	5.05	2.20	
73.51	370	2.16	1.99	
76.44	370	1.85	2.38	
77.65	370	1.36	2.55	
76.14	370	1.37	2.33	
72.4	370	2.5	1.91	
70.32	370	1.86	1.99	
76.16	370	1.06	2.33	
72.75	370	2.6	1.93	
73.83	370	2.52	2.02	
78.68	370	1.45	2.68	
75.32	370	2.79	2.21	
91.85	15100	-2.15	-5.11	3.97
91.42	15100	-4.27	-4.36	
96.65	3700	-8.02	-14.24	

Evaluation of the Field Performance of Chip Seal and Microsurfacing

Data Sets 8 and 9 in Table 17 were used to calculate the Performance Jump (PJ), Deterioration Rate Reduction (DRR), Effectiveness (EF), and Increase in PSL (ΔPSL) for the chip seal and microsurfacing control sections.

Performance Jump (PJ)

Figure 46 presents the PJ for the different performance indices as a function of the relevant pre-treatment pavement condition for chip seal and microsurfacing. As shown in this figure, chip seal and microsurfacing were most effective in immediately improving the RCI and RTI, respectively, because the slopes and intercepts were greater as compared to the other indices, which is in line with the findings from previous studies *[41, 44]*. It is also clear that for the chip seal and microsurfacing, the PJ for RCI and RTI, respectively, were highly correlated to the relevant pre-treatment pavement conditions as supported by R^2. Therefore, these linear regression models could be used to predict the PJ based on the pre-treatment pavement conditions. This is an important issue in PMS to quantify the immediate improvement in the distress indices after treatment application.

For chip seal, 98% of the log miles exhibited a positive PJ for RCI with a mean of 17.4 ± 11.8, whereas the mean PJ for RFI and PCI was 3.6 and 11.0, respectively. This indicates that chip seal had a negligible effect on improving the pavement roughness, which is consistent with the findings of other studies *[86]*. Unlike chip seal, microsurfacing was found to be statistically significant in initially improving all the condition measures that are usually associated with this type of treatment. About 94% of the log miles exhibited a positive PJ for RTI with a mean of 17.0 ± 14.4, whereas the mean PJ for RFI and PCI were 11.4 and 15.2, respectively.

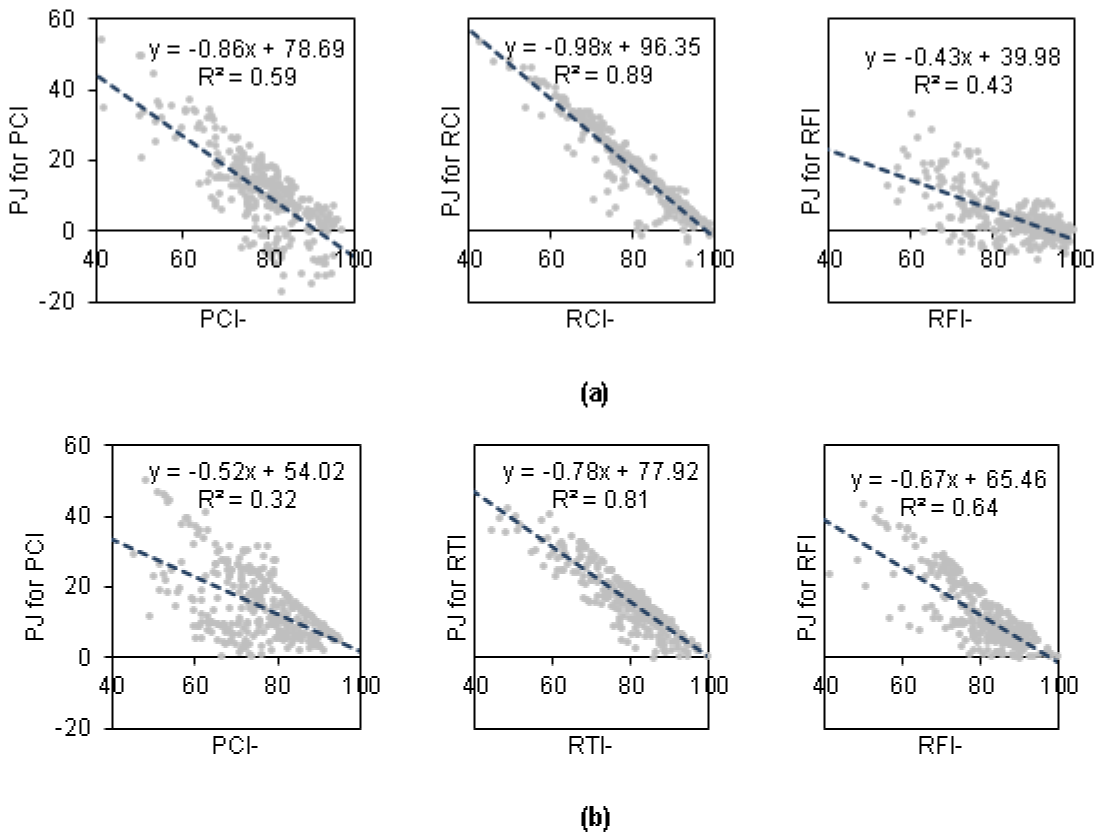
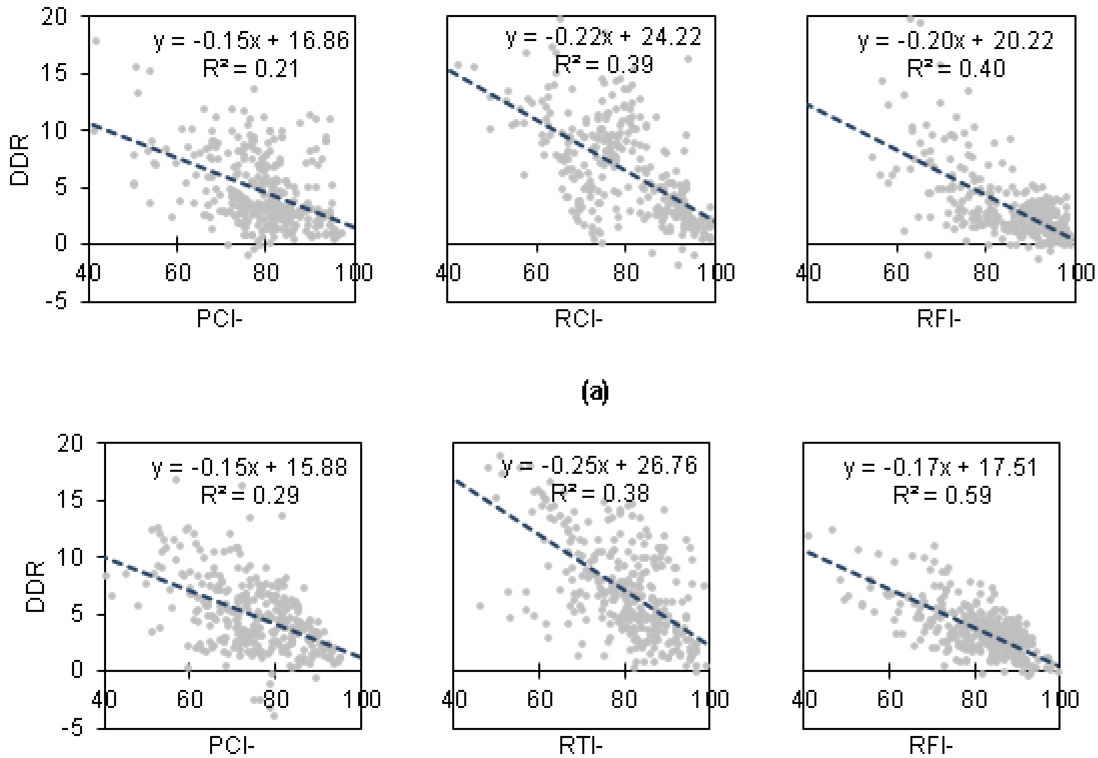


Figure 46

Performance jump due to (a) chip seal and (b) microsurfacing as a function of the pre-treatment pavement conditions

Deterioration Rate Reduction (DRR)

The DRR was calculated for each log mile in Data Sets 8 and 9 in Table 17 using equation (9); see Figure 47. To facilitate the analysis of the plotted data in Figure 47, the average DRR was calculated for each treatment and for each pavement condition index as presented in Figure 48. In line with the PJ results, DRR analysis also showed that chip seal and microsurfacing are most effective in immediately improving the RCI and RTI, respectively. In addition, chip seal slowed down the development of random cracks by 6.38 units/year and microsurfacing slowed down the deterioration of rutting condition by 7.43 units/year.



(b)

Figure 47

Deterioration rate reduction for (a) chip seal and (b) microsurfacing versus the pre-treatment pavement conditions

For more information, please contact PI Mostafa Elseifi at 225-578-4821.

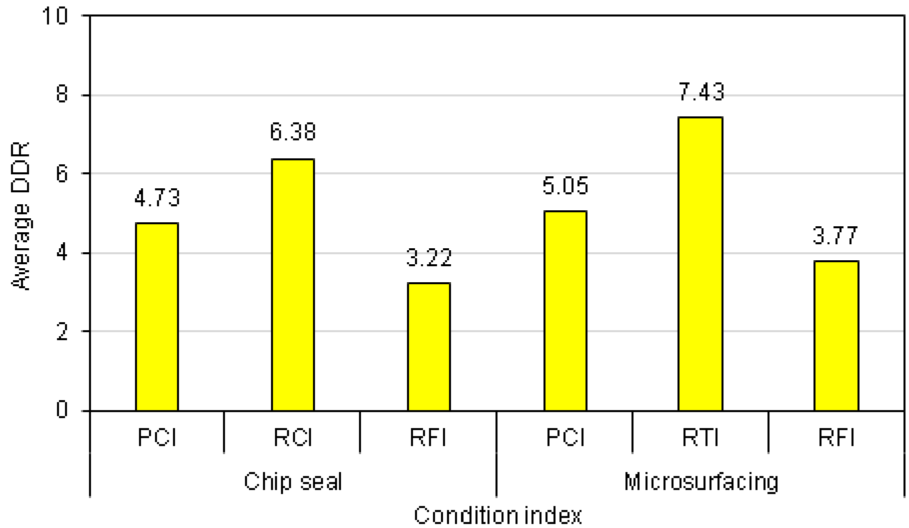
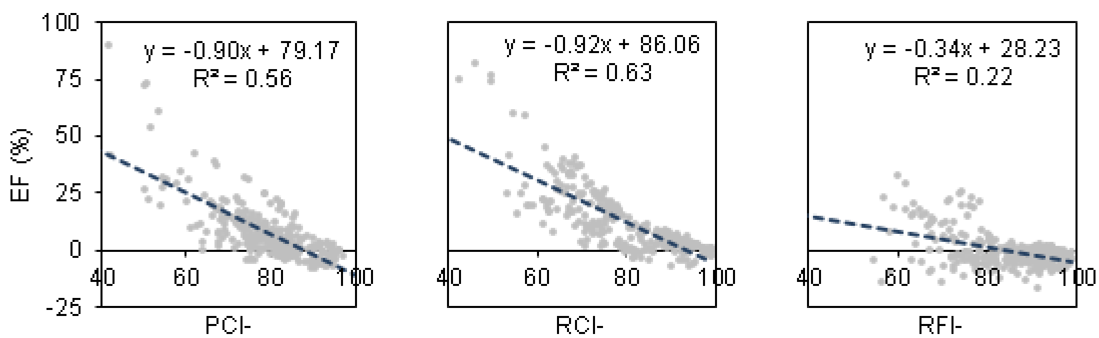


Figure 48

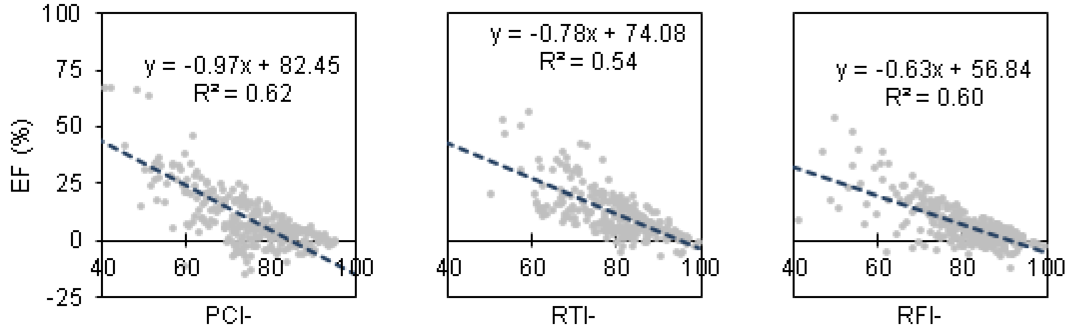
Average DRR in pavement condition indices due to treatment application

Effectiveness (EF)

The Effectiveness (EF) was calculated for each log mile in Data Sets 8 and 9 in Table 17 using equation (11); see Figure 49. To facilitate the analysis of the plotted data in Figure 49, (a) the percentage of positive points and (b) the average EF (including the positive and negative values), were calculated for each treatment and condition index. Based on these two measures, a ranking was proposed for each condition index as shown in Table 21. As shown in Table 21, the long-term effectiveness of chip seal was highest for RCI followed by PCI followed by RFI, while the long-term effectiveness of microsurfacing was highest for RTI followed by PCI followed by RFI.



(a)



(b)

Figure 49
Effectiveness for (a) chip seal and (b) microsurfacing versus the pre-treatment pavement conditions

Table 21
Summary of the EF results

Treatment	Condition Index	Percentage of positive points (%)	Average EF (%)	Ranking
Chip seal	PCI	79	8.0	2
	RCI	90	11.9	1
	RFI	32	-0.6	3
Microsurfacing	PCI	79	10.0	2
	RTI	95	11.3	1
	RFI	83	6.7	3

To evaluate the effect of traffic, precipitation, and AC thickness on the long-term effectiveness of chip seal and microsurfacing, the EF for PCI was grouped by the traffic load factor (ADTX), precipitation load factor (AAPX), and AC thickness and the average value was calculated for each group; see Figure 50. It should be noted that ADTX and AAPX were calculated as follows:

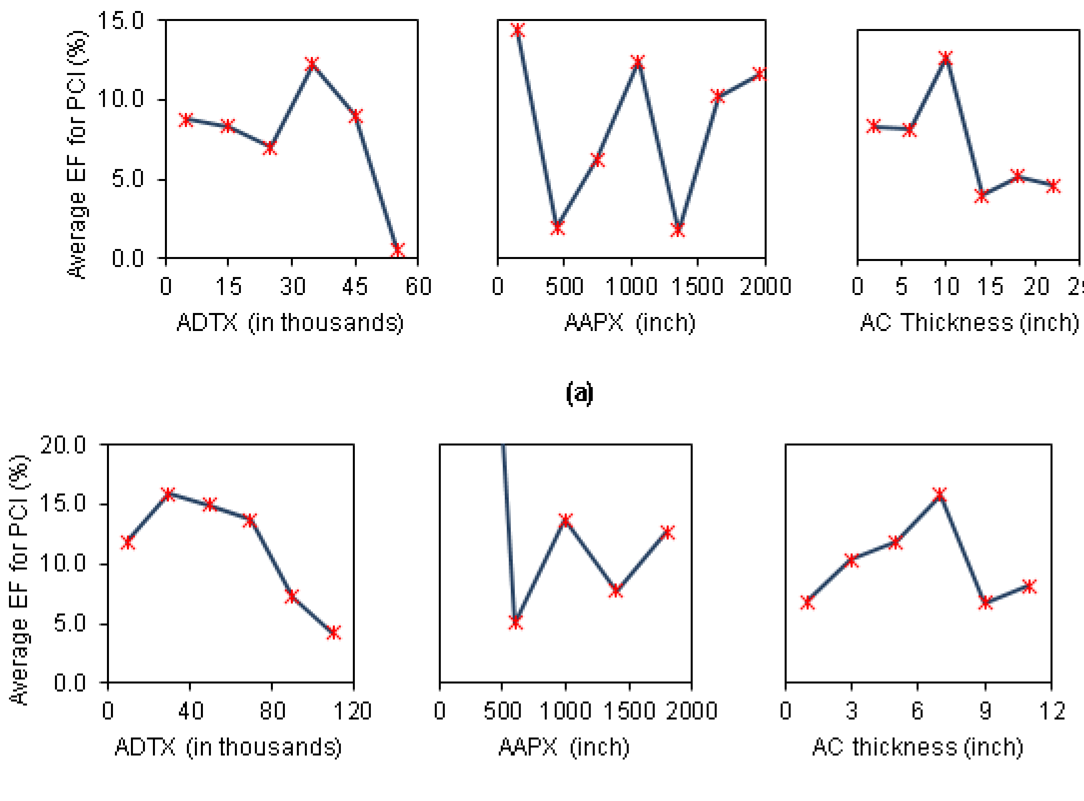
$$\mathrm{ADTX} = \mathrm{ADT} \times \mathrm{t_x} \quad (25)$$

$$\mathrm{AAPX} = \mathrm{AAP} \times \mathrm{t_x} \quad (26)$$

where,
ADT= Average daily traffic;
AAP= Average annual precipitation; and

t_x= Time from the last major maintenance activity till chip seal or microsurfacing application.

As shown in Figure 50, for microsurfacing treatments, the effect of traffic load on the effectiveness shows that EF increases up to a certain point and then starts to drop sharply as traffic load increases. The microsurfacing effectiveness is optimized when applied to pavements with ADTX less than 70,000. On the other hand, EF did not exhibit a clear pattern with ADTX for the sections with chip seal. Yet, for chip seal, optimum effectiveness was observed when applied to pavements with ADTX of approximately 35,000. For chip seal and microsurfacing, sections receiving precipitation (AAPX) less than 500 in. had a significantly higher efficiency as compared to the sections receiving higher precipitation load, although no definite relationship was observed. EF increased with increasing AC layer thicknesses (a) up to a thickness of 10 in. for chip seal treatments, where an EF of 13.2% was obtained, and (b) up to a thickness of 7 inch for microsurfacing where the optimum EF was estimated to be 15.7%.



(b)

Figure 50

Average EF for PCI of (a) chip seal, and (b) microsurfacing treatment as a function of traffic, precipitation, and AC thickness

Increase in PSL (ΔPSL)

The increase in PSL (ΔPSL), in terms of PCI, was calculated for each log mile in Data Sets 8 and 9 shown in Table 17 using equation (14). The calculated ΔPSL was then grouped based on the pre-treatment pavement conditions (PCI^-) and the average ΔPSL was calculated for each group as presented in Figure 51. As shown, when applied to pavements with $PCI^-<90$, chip seal extended the service life of the pavements by 6.4 to 10.5 years, while microsurfacing extended the service life of the pavements by 4.9 to 8.8 years. Comparing ΔPSL in relation to PCI^-, ΔPSL is maximum when applied to pavements with PCI values ranging from 70 to 75 for chip seal and 80 to 85 for microsurfacing applications. Therefore, it was concluded that chip seal is more effective for pavements that are in fair conditions while microsurfacing is more effective for pavements in good existing conditions. Yet, as shown in Figure 51, microsurfacing applied to pavements with $PCI^->90$ did not extend the PSL. This conclusion is similar to the conclusion drawn in the previous section for crack sealing.

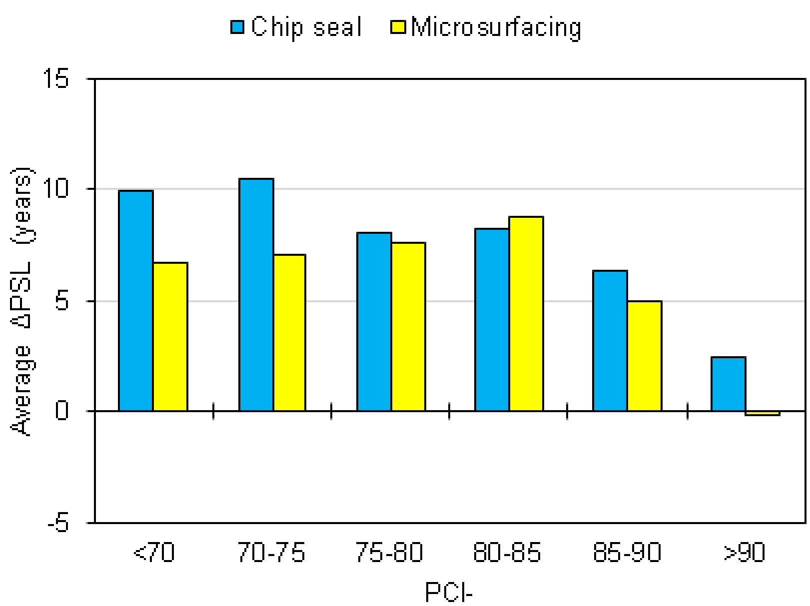


Figure 51
Average ΔPSL as a function of pretreatment condition of the pavements

The calculated ΔPSL was then regrouped based on the geographical location in Louisiana and the average ΔPSL was calculated for each district as presented in Figure 52. As shown, the treatments applied in different geographical areas in Louisiana did not show large variation in ΔPSL, as the mean values ranged from 6.1 to 11.6 years for chip seal and 5.7 to 7.9 years for microsurfacing. For all the districts, chip seal performed better than microsurfacing except for District 2 where microsurfacing ΔPSL exceeded chip seal by about 2 years.

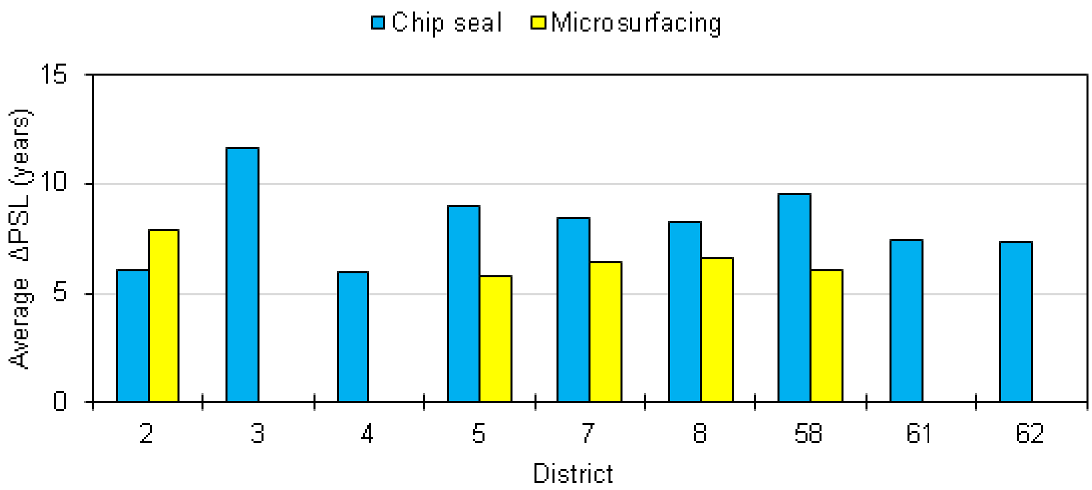
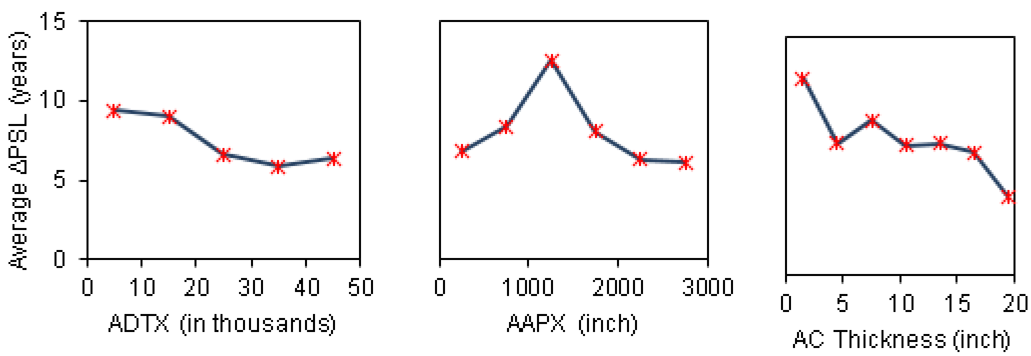
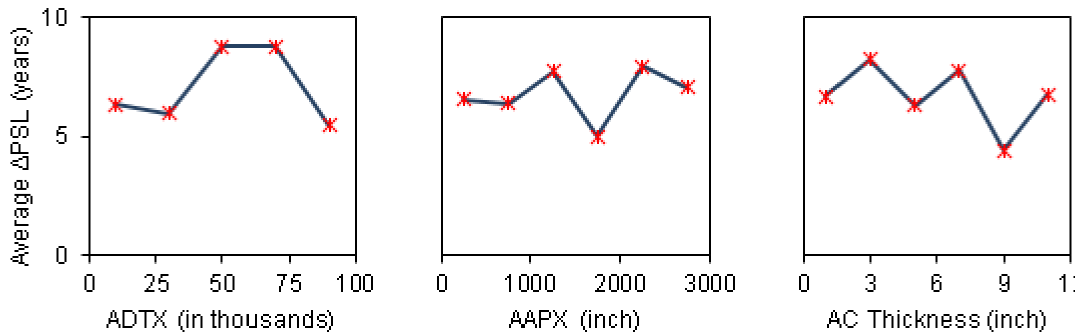


Figure 52
Average ΔPSL due to treatment applications at different districts in Louisiana

The calculated ΔPSL was then regrouped by ADTX, AAPX, and AC thickness and the average value was calculated for each group; see Figure 53. The effect of traffic on ΔPSL was found to be similar to its effect on the long-term effectiveness (EF), shown in Figure 50. As shown in Figure 53, microsurfacing had an optimum ΔPSL of 8.8 years when ADTX values ranged from 50,000 to 70,000, whereas for chip seal, an optimum ΔPSL of 8.9 years was observed for ADT<15,000. Yet, no definite trend in ΔPSL was observed for varying AC layer thickness and precipitation load.



(a)



(b)

Figure 53
Average ΔPSL of (a) chip seal, and (b) microsurfacing treatment as a function of traffic, precipitation, and AC thickness

Evaluation of the AC Overlays Service Lives

The research team calculated the PSL for Data set 10 in Table 17, in terms of PCI, RCI, RTI, and RFI. In Louisiana, candidate projects for AC overlays are selected based on fund availability and trigger values. Therefore, in these calculations, a threshold index of 60 was used for all the distresses to match the selection scheme used by DOTD *[69]*. For each data point (project), the lowest PSL of the four indices was selected as the critical PSL (PSL_C) for this specific project and the corresponding distress was reported as the limiting (i.e., controlling) distress. As shown in Figure 54, random cracking was the limiting distress for 49% of the projects, rutting was the limiting distress for 30% of the projects, and roughness was the limiting distress in only 8% of the projects.

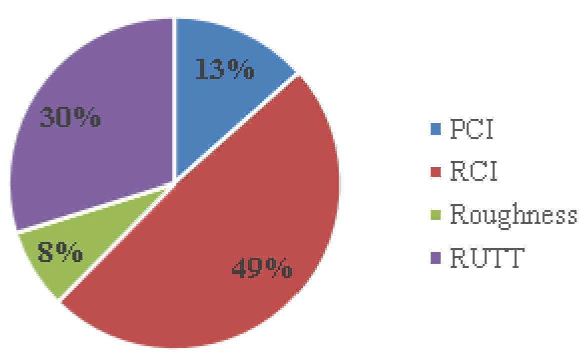


Figure 54
Limiting distresses in the analyzed projects

For all the projects in Data Set 10, the average PSL was 22.1 ± 8, 20.3 ± 8, 29.1 ± 10, and 20.2 ± 7.5 years for PCI, RCI, RFI, and RTI, respectively. Figure 55 presents the average PSL categorized based on the pretreatment pavement conditions. The general trend in Figure 55 indicates that longer PSL is achieved with better pre-treatment pavement conditions.

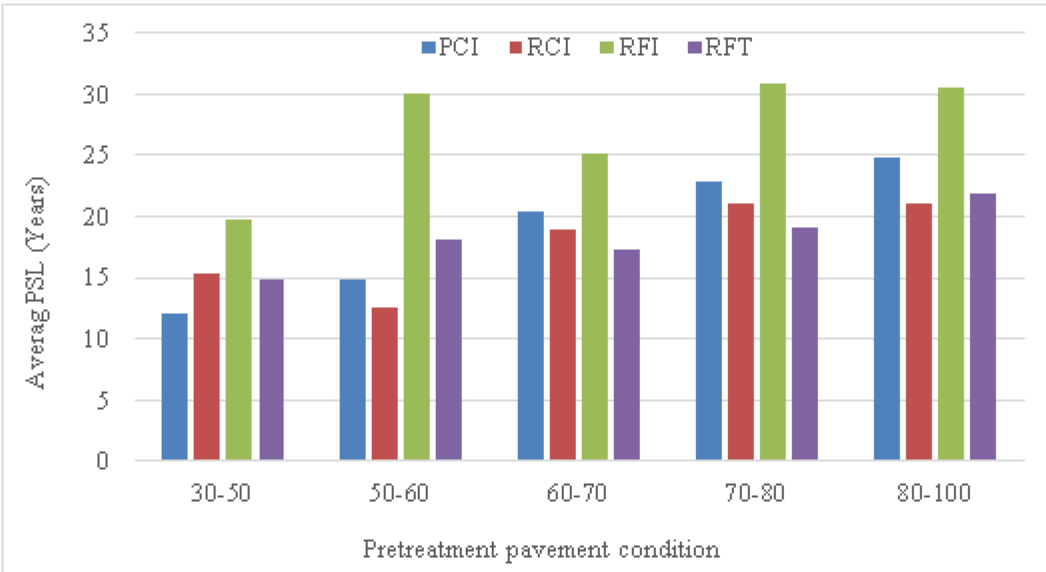


Figure 55
Relationship between average PSL and pretreatment pavement conditions

When the PSL for the different projects was plotted against ADT, no clear trend was observed, possibly because the projects had different overlay thicknesses and pre-treatment pavement conditions, which seemed to be the most significant factors affecting the PSL. Therefore, 11 pairs of projects with the same overlay thickness, same PCI^-, but different ADT, were identified. These projects were compared to evaluate the effect of ADT on PSL of PCI; see Figure 56 (a, b, and c). For most of the pairs, projects with lower ADT exhibited lower PSL than projects with high ADT. Yet, statistical t-tests showed that for all the overlay thicknesses, this difference was insignificant indicating that traffic levels had minimal effect on PSL for PCI. This finding agrees with a study conducted in Florida, which has similar climatic conditions to Louisiana *[87]*. Three projects with the same PCI^-, ADT, but different overlay thicknesses were selected to evaluate the impact of overlay thickness on the resulting PSL for PCI, see Figure 56 (d). As expected, higher PSL was achieved with greater overlay thicknesses.

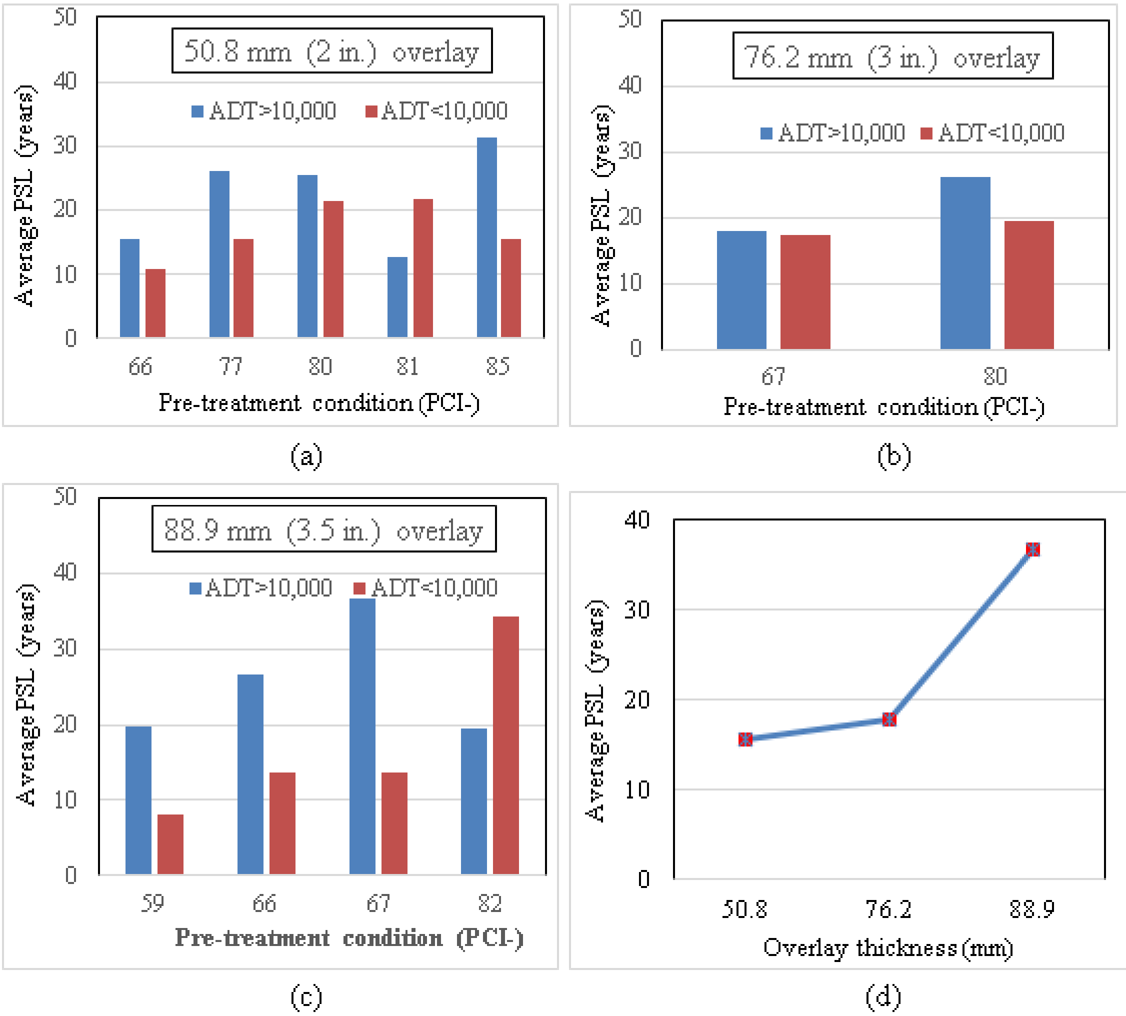


Figure 56

(a), (b), and (c) Average PSL versus PCI- for different overlay thicknesses (d) Average PSL versus overlay thickness under high traffic level

Since the overlay thickness primarily affects the pavement service life, the research team classified all the projects in Data Set 10 in Table 17 into four groups based on the AC overlay thickness. For each group, the average PSL and 95% confidence intervals were calculated as shown in Table 22. This table could be used in Louisiana to determine the expected PSL knowing the AC overlay thickness. This is an important issue in PMS during the cost-benefit analysis of maintenance treatments applied on AC overlays.

Table 22

Lower and upper 95% confidence intervals and average overlay PSL (in years) for difference thickness classes

Descriptive statistics	AC overlay thickness class			
	<=2 inch	>2 inch to <=3 inch	>3 inch to <=4 inch	>4 inch
Average	15.5	16.4	17.2	19.8
Upper interval	16.9	18.3	18.7	27.0
Lower interval	14.0	14.4	15.7	12.5

Cost Benefits Analysis

Cost Effectiveness of Maintenance Treatments for a Single Maintenance Cycle

The EAC, B/C, and CE were calculated for each data point in Data Sets 7, 8, and 9. The results of the previous tasks indicated that crack sealing improves only the random cracking of the pavement, while chip seal and microsurfacing improve most of the pavement conditions. Therefore, all the calculations in this section for crack sealing were conducted in terms of RCI, while all the calculations for chip seal and microsurfacing were in terms of PCI. Therefore, the cost-effectiveness of chip seal was compared to that of microsurfacing. It is recommended not to compare the cost-effectiveness of crack sealing with that of chip seal or microsurfacing in this section since crack sealing is expected to be applied in different situations from chip seal and microsurfacing (i.e., crack sealing should be applied to treat only surface cracks when no significant rutting or roughness exist).

The computed EAC, B/C, and CE for each maintenance treatment was then categorized based on the pre-treatment pavement conditions (RCI^- for crack sealing and PCI^- for chip seal and microsurfacing) and the average was calculated. Since previous tasks indicated that the maintenance treatments applied to pavements in very good conditions (PCI or RCI greater than or equal 90) exhibit no or negligible benefits, the pretreatment pavement conditions in this section were grouped as follows: (a) <77, (b) 77-80, (c) 81-84, and (d) 85-89.

Equivalent Annual Cost (EAC). Figure 57 shows the average EAC for each maintenance treatment versus the pretreatment pavement conditions. For crack sealing, the lowest EAC was achieved for RCI^- group “81-84”. The EAC increased towards RCI^- group “85-89” and towards RCI^- groups “77-80” and “<77.” This indicates that the optimum timing of crack sealing, in terms of EAC, is when RCI^- is between 81 and 84. Chip seal and microsurfacing showed the same trend where the highest EAC was achieved for PCI$^-$ group "85-89". The EAC decreased towards lower groups of PCI$^-$ indicating that the cost-effectiveness of chip seal and microsurfacing, in terms of EAC, is maximized when applied to pavements in poor surface conditions. Comparing the results of chip seal and microsurfacing, chip seal had lower EAC and therefore, was more cost effective than microsurfacing for all the PCI$^-$ groups.

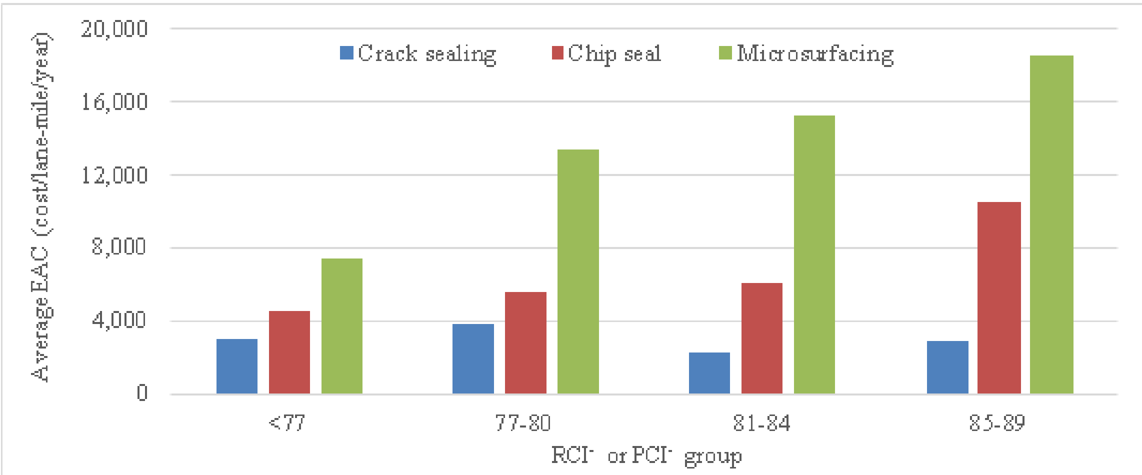


Figure 57
Average EAC versus pretreatment pavement condition

Benefit Cost Ratio (B/C). A sample calculation of the B/C for one of the data points is provided in Appendix B. Figure 58 shows the average B/C for each maintenance treatment versus the pre-treatment pavement conditions. Since the B/C for all the groups was greater than one, it could be concluded that all the treatments are cost-effective regardless of the pre-treatment pavement conditions. The trend of B/C for crack sealing was nearly similar to the trend of EAC for crack sealing, where the highest B/C (most cost-effective scenario) was obtained for the "81-84" group and decreased towards RCI$^-$ group "85-89" and towards RCI$^-$ groups "77-80" and "<77". This indicates that the optimum timing of crack sealing, in terms of B/C, is when RCI$^-$ is between 81 and 84. Similarly, the trend of B/C for chip seal and microsurfacing was similar to the trend for EAC where the highest B/C was achieved for PCI$^-$ group "<77". This B/C decreased towards higher groups of PCI$^-$ indicating that the cost-effectiveness of chip seal and microsurfacing, in terms of B/C, is maximized when applied to pavements in poor surface conditions. Comparing the results of chip seal and microsurfacing, chip seal had a higher B/C ratio and therefore, was more cost effective than microsurfacing for all the PCI$^-$ groups.

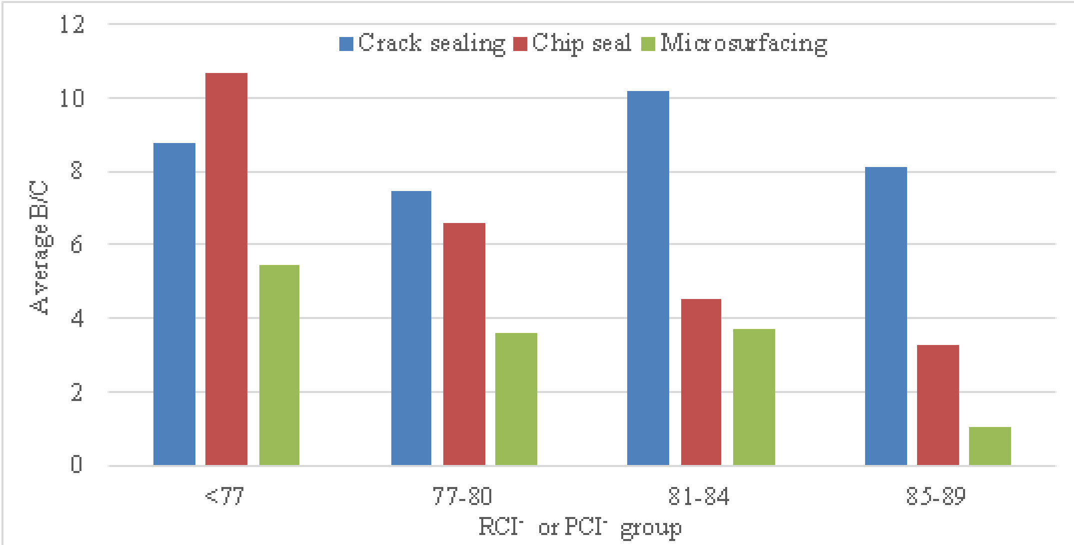


Figure 58

Average B/C versus pretreatment pavement condition

Cost Effectiveness (CE). Figure 59 presents the average CE for each maintenance treatment versus the pre-treatment pavement conditions. For crack sealing, the highest CE (most cost-effective scenario) was obtained for the "85-89" group and decreased towards lower RCI^- groups. For chip seal, the highest CE was obtained for the "77-80" group and slightly decreased towards lower and higher PCI^- groups. For microsurfacing, the highest CE was obtained for the "81-84" group and decreased towards lower and higher PCI^- groups. Comparing between the results of chip seal and microsurfacing, chip seal was more cost-effective than microsurfacing for all the pre-treatment pavement condition groups.

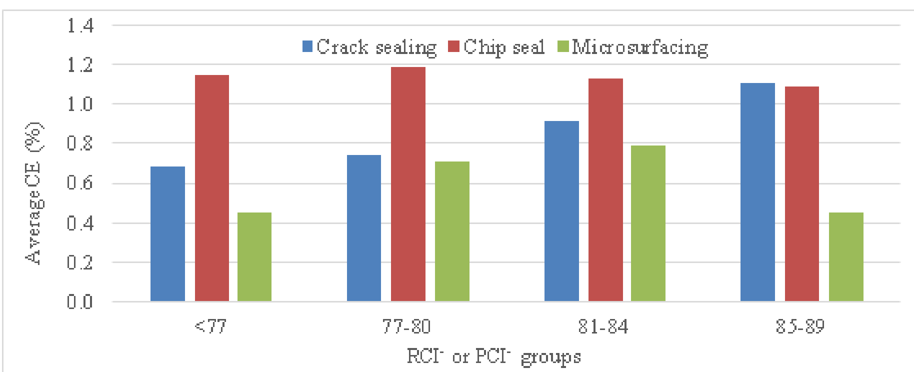


Figure 59

Average CE versus pretreatment pavement condition

Model Development for the Treatment Net Benefits (TNBs). Positive TNBs calculated in the previous section for crack sealing (Data Set 7) were analyzed to develop a model that predicts the positive TNB of crack sealing based on RCI^-, AC overlaid pavement type (flexible or composite), pavement age at sealing date (A), ADT, and the expected ΔPSL. The predicted TNB could be then divided by the expected project unit cost to determine the CE. ANOVA was conducted between the TNB and these five variables as shown in Table 23. The results indicated that all the parameters, except pavement type, were statistically correlated to the TNB. Therefore, RCI^-, A, ADT, and ΔPSL were considered in the regression model.

Table 23
Results of ANOVA

Variables	**P-value**	**Interpretation**
RCI^-	< 0.001	Significant
Pavement type	0.6	Not Significant
A	< 0.001	Significant
ADT	< 0.001	Significant
ΔPSL	< 0.001	Significant

A total of 117 data points were used in the model development. About 80% of the data (94 points) were used to fit the model and 20% of the data (23 points) were used to validate and test the model. The fitted model developed after performing non-linear regression analyses on the crack sealing TNB as a dependent variable, and with RCI^-, A, ADT, and ΔPSL as the independent variables were as follows:

$$\mathbf{TNB} = (40.76*RCI^-) + (-0.504*\{RCI^-\}^2) + (0.00217683805844751*\{RCI^-\}^3) + (-175.9*A) + (22*A^2) + (-0.881396949287229*A^3) + (0.009*ADT) + (-1.466\ e\text{-}06*ADT^2) + (5.1\ e\text{-}11*ADT^3) + (21.4*\Delta PSL) + (-0.971*\Delta PSL^2) + (0.03013630001*\Delta PSL^3) + (-703.523) \quad (27)$$

where ADT<=15,100, and $70 < RCI^- < 100$.

Figures 60 and 61 present the actual and predicted TNB using the fitting data and test data, respectively. The proposed model predicted TNB with an acceptable level of accuracy as supported by R^2 and RMSE shown in the figures. For the fitting data, the R^2 and RMSE were 0.90 and 20.3, respectively, while for the test data, the R^2 and RMSE were approximately 0.83 and 27.1, respectively.

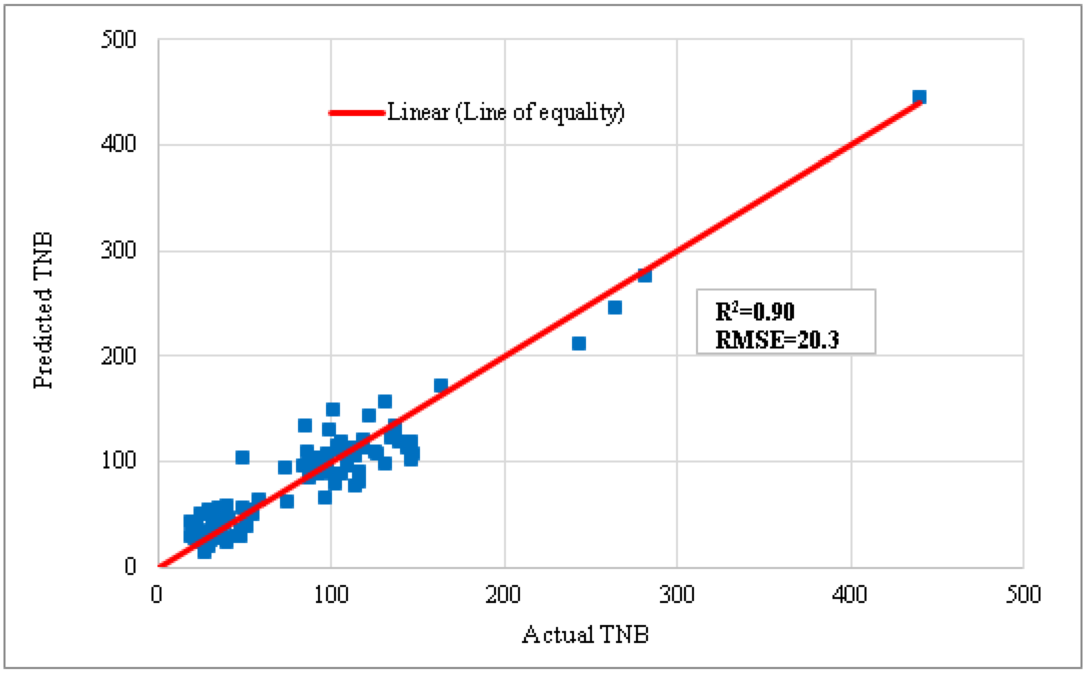


Figure 60
Predicted TNB versus actual TNB using fitting data

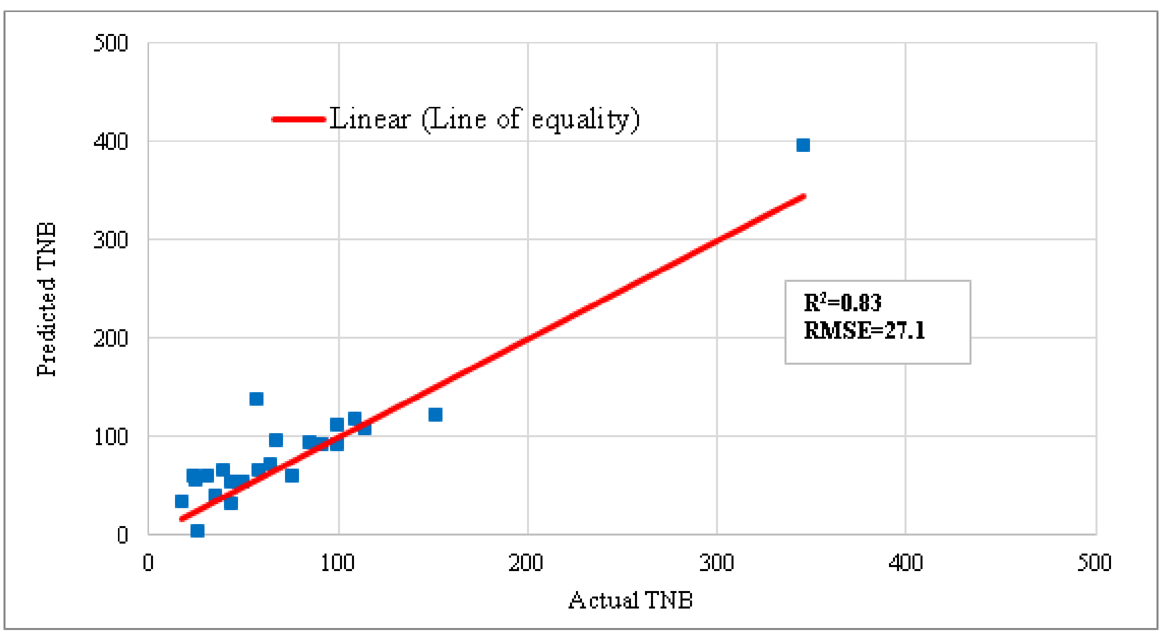


Figure 61
Predicted TNB versus actual TNB using independent validation data

Cost Effectiveness of Maintenance Treatments for Multiple Maintenance Cycles

Table 24 summarizes the input parameters used in the case study. The total NPV was calculated for all the scenarios described in Table 10 and the results are presented in Figure 62. Sample calculation of the total NPV for scenario 2c is provided in Appendix C. Comparing Strategy 1 with all the other strategies in Figure 62, Strategy 1 had the highest total NPV for all cases of pre-treatment conditions (scenarios 1 a through d) indicating that it should be avoided.

Comparing strategies 3 through 6, it is clear that strategy 3 had the lowest NPV for all the PCI^- indicating that successive chip seal treatments is the most cost-effective long-term strategy. Comparing the results of strategy 3 at different PCI^- (scenarios 3 a through d), scenarios a, b, and c had the lowest NPV indicating that this strategy is most cost-effective when chip seals are applied when the PCI of the existing pavement reaches 75, 79, or 82. Comparing the results of strategy 2 at different RCI^- (scenarios 2 a through d), scenario c followed by d had the lowest NPV indicating that this strategy is the most cost-effective when crack sealing is applied when the RCI of the existing pavement reaches 82 or 87. It is worth noting that these conclusions are specific to the considered case study and may change with the variations in the parameters shown in Table 24.

Table 24
Input parameters used in the case study

Input Class	Input	Value
General Data	ADT, vehicles per day	2,000
	Discount Rate, %	4
	Base year in the analysis	2018
	Analysis period, years	50
AC overlay Data	AC overlaid pavement type	Flexible
	Year at which the first overlay was applied	2005
	First AC overlay (in year 2005) unit cost ($/lane-mile)	200,000
	AC overlay thickness (inch)	3
	PSL1 of AC overlay (years)	21
	AC overlay unit cost in 2018 ($/lane-mile)	300,000
	Immediate RCI or PCI after AC overlay application	95
	Threshold RCI or PCI for AC overlay application	60
Crack sealing data	Crack sealing unit cost in 2018 ($/lane-mile)	12,000
Chip seal Data	Chip seal unit cost in 2018 ($/lane-mile)	20,000
Microsurfacing Data	Microsurfacing unit cost in 2018 ($/lane-mile)	40,000

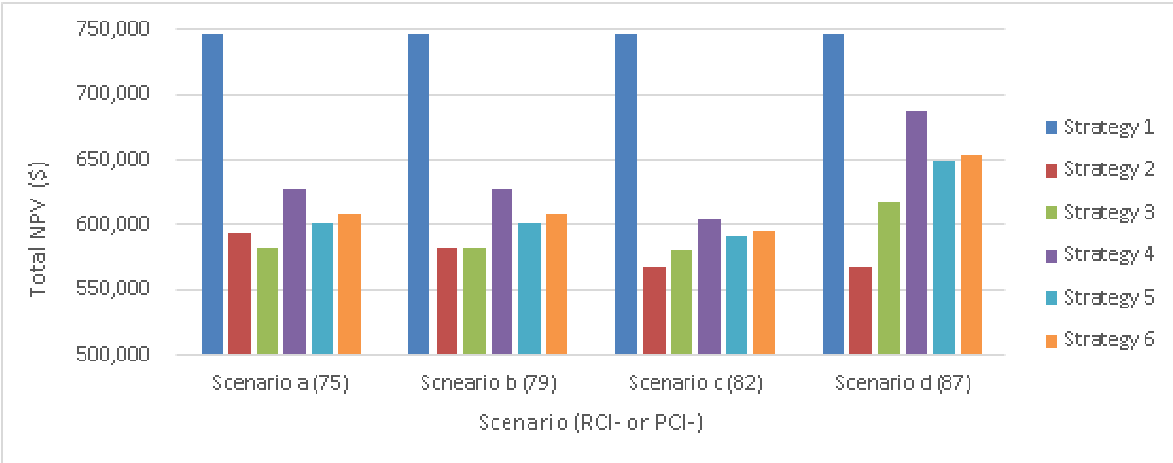


Figure 62
Total NPV for the different scenarios

Summary

The entire results of the cost-benefit analyses for the field projects and case study were compiled and analyzed to provide the final recommendation with respect to the application timing of crack sealing, chip seal, and microsurfacing. Table 25 summarizes the recommended optimal timing for each maintenance treatment, in terms of RCI^- for crack sealing and PCI^- for chip seal and microsurfacing, based on each economic indicator.

Table 25
Optimal timing of maintenance treatments

Economic Indicator	Crack Sealing	Chip seal	Microsurfacing
EAC	"81-84"	"50-77"	"50-77"
B/C	"81-84"	"50-77"	"50-77"
CE	"85-89" followed by "81-84"	"50-77" or "77-80"	"81-84" followed by "77-80"
NPV	"81-84" followed by "85-89"	"50-77" or "77-80" or "81-84"	"81-84 followed by "50-77"
Optimal timing	"81-89" preferably "81-84"	"50-77"	"50-84"

Laboratory Testing for Cores Extracted from the Experimental Program

Lottman Test

The results of the Lottman test for groups B, C, D, and E are presented in Figure 63. As shown in this figure, the critical soaking time (t_s) corresponding to a TSR of 80% was about 1.3 days. This value was used in the following sections to assist in evaluating the effect of crack sealing on moisture damage.

Asphalt Saturated Hydraulic Conductivity

This test was conducted in accordance to Florida's test method FM 5-565 after soaking the asphalt cores in water for two hours and the resulting K_{sat} for the three cores was measured to be 3.5×10^{-8} m/s.

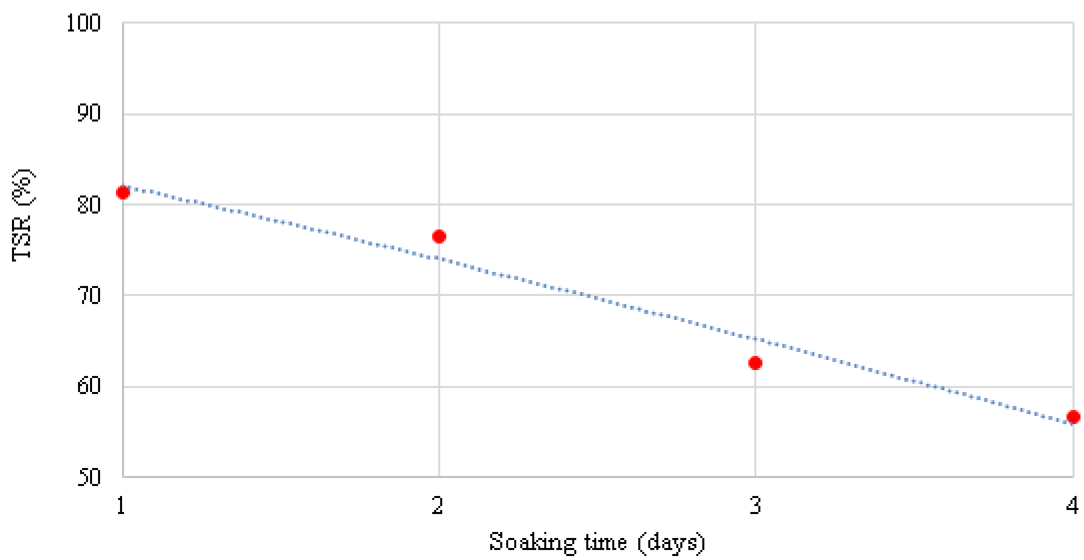


Figure 63
Results of the Lottman test

Evaluate the Effect of Crack Sealing on Moisture Damage

Results of the Calibration of the Finite Element Model

Steady-State Analysis. The initial field Volumetric Moisture Content (VMC) at the mid-depth of the base was computed based on GPR data from the initial site visit. Travel times, determined from the A-scan at log-mile 1.6, were used to calculate the base dielectric constant; which was 16.9. This value was then used to compute the field VMC using the

Topp equation *[88]*. The calculated field VMC (0.30) was compared with the predicted value for the steady-state analysis (0.24). The difference between the field and predicted values was attributed to the possible error in measuring the water levels in the side ditches. Such error would affect the computed GWT level, which in turn may affect the predicted VMC. To address this discrepancy, water levels in both ditches were adjusted in the FE model until the predicted VMC was increased to 0.31, which was close to the field VMC. Figure 64 shows the final water levels in the side ditches and GWT elevation after calibration. To validate these results, the GPR line-scans at log-mile 1.6, shown in Figure 65, showed strong reflections at 0.6 m; these strong reflections are generally due to the GWT *[89]*.

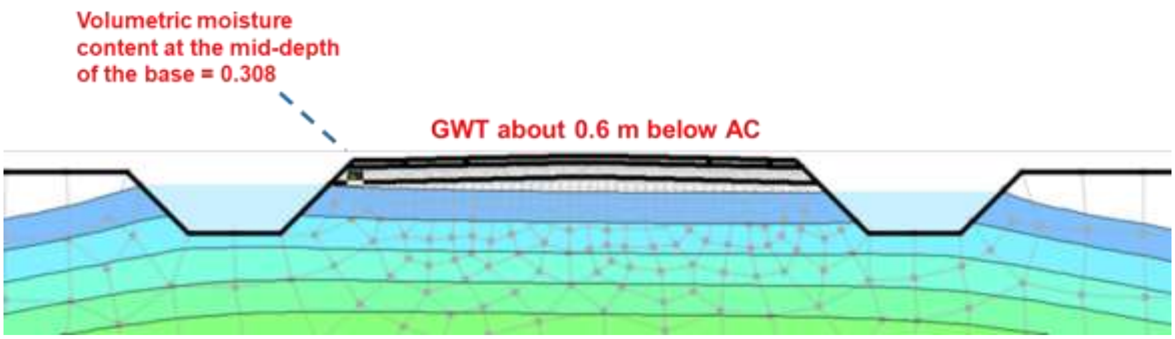


Figure 64
Zero and negative pore-water pressure contours for the steady-state analysis

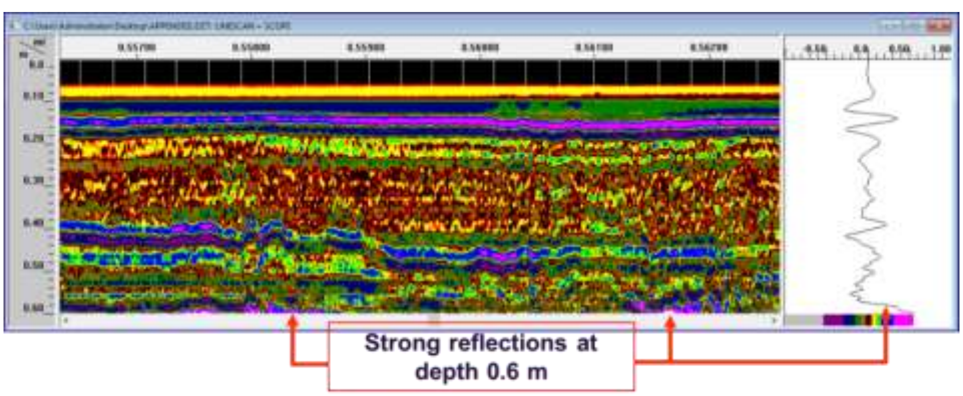


Figure 65
GPR line scan at log-mile 1.6

Transient State Analyses. Subgrade samples taken 14 days after the first site visit were tested in the laboratory and indicated a field VMC of 0.18. This value was similar to the predicted value at day 14 of 0.19. However, the field VMC of 0.23 was obtained for the base layer on the second site visit using GPR data. This value was significantly higher than the predicted value at day 308 (0.10). The reason for these differences in the field and predicted VMC values could be that the K_{sat} of the base and subgrade were adopted from previous studies and were not measured values. For this reason, K_{sat} for these layers along with the Van Genuchten parameter "a" for the AC layer, were slightly adjusted until the predicted VMC values converged to the field values. This process resulted in predicted VMC values of 0.19 and 0.18 for the base and subgrade, respectively. This approach was previously adopted for model calibration in Ohio and Minnesota *[78, 79]*.

Results of the Sensitivity Analysis

Effect of Asphalt Saturated Permeability and Rain Intensity on Crack Sealing. The amount of water reaching the crack tip of the crack-sealed asphalt pavement primarily depends on the asphalt layer saturated permeability (AC K_{sat}) and rain intensity (R). Therefore, a wide range of AC K_{sat} and R were simulated in the analysis and the corresponding saturation under the crack tip of the sealed FE model was calculated. In Louisiana, 97% of the hours of the year experience rain intensity ranging between 0 and 0.1 in/hr.; therefore, R values of 0.01, 0.05, and 0.1 were simulated. Similarly, AC K_{sat} ranging between $1.0x10^{-5}$ and $9.2x10^{-8}$ m/s were simulated to include the typical range of permeability of dense-graded asphalt mixes as reported in previous studies *[90, 91]*. Figure 66 shows the saturation distribution in the sealed model after rain for two runs having similar R of 0.1 in/hr. and AC K_{sat} of $1.0x10^{-5}$ and $9.2x10^{-8}$ m/s.

When the AC K_{sat} was $1.0x10^{-5}$ m/s, the crack-tip became fully-saturated after four hours of rain because the water reached the crack tip quickly through the permeable pavement structure. When the AC K_{sat} was $9.2x10^{-8}$ m/s, the crack tip remained partially saturated after rain because the water did not reach the crack tip either through the sealed cracks or impermeable pavement structure. Consequently, simulation runs were conducted considering the aforementioned range of AC K_{sat} values to estimate the critical AC K_{sat} ($K_{critical}$) that would prevent water from reaching the crack-tip. This process was repeated for different R values. The results indicated that for all the R values, $K_{critical}$ is about $2x10^{-6}$ m/s.

Louisiana specifies 19-mm Nominal Maximum Aggregate Size (NMAS) and a lift thickness between 40 and 50 mm for wearing course mixtures *[92]*. A recent study in Louisiana indicated that the permeability of such mixes vary widely between $6.8 x10^{-5}$ m/s and $1x10^{-8}$ m/s depending on the air voids, lift thickness, and gradation. Therefore, the authors developed a regression model to predict the permeability of conventional 19-mm NMAS wearing course mixtures in Louisiana knowing the air voids, lift thickness and gradation as follows *[92]*:

$$K = 10^{-4}\{76.6\ (\%\ Air\ voids) - 17.2\ P_{0.075} + 163.4\ P_{0.3} - 197.5\ P_{0.6} + 33.2\ P_{2.36} + 4.5\ P_{12.5} - 1.7\ L\} \quad (28)$$

where,

K = coefficient of permeability (mm/s);

$P_{0.075}$ = the percent passing 0.075-mm sieve;

$P_{0.3}$ = the percent passing 0.3-mm sieve;

$P_{0.6}$ = the percent passing 0.6-mm sieve;

$P_{2.36}$ = the percent passing 2.36-mm sieve;

$P_{12.5}$ = the percent passing 12.5-mm sieve; and

L = the lift thickness (mm).

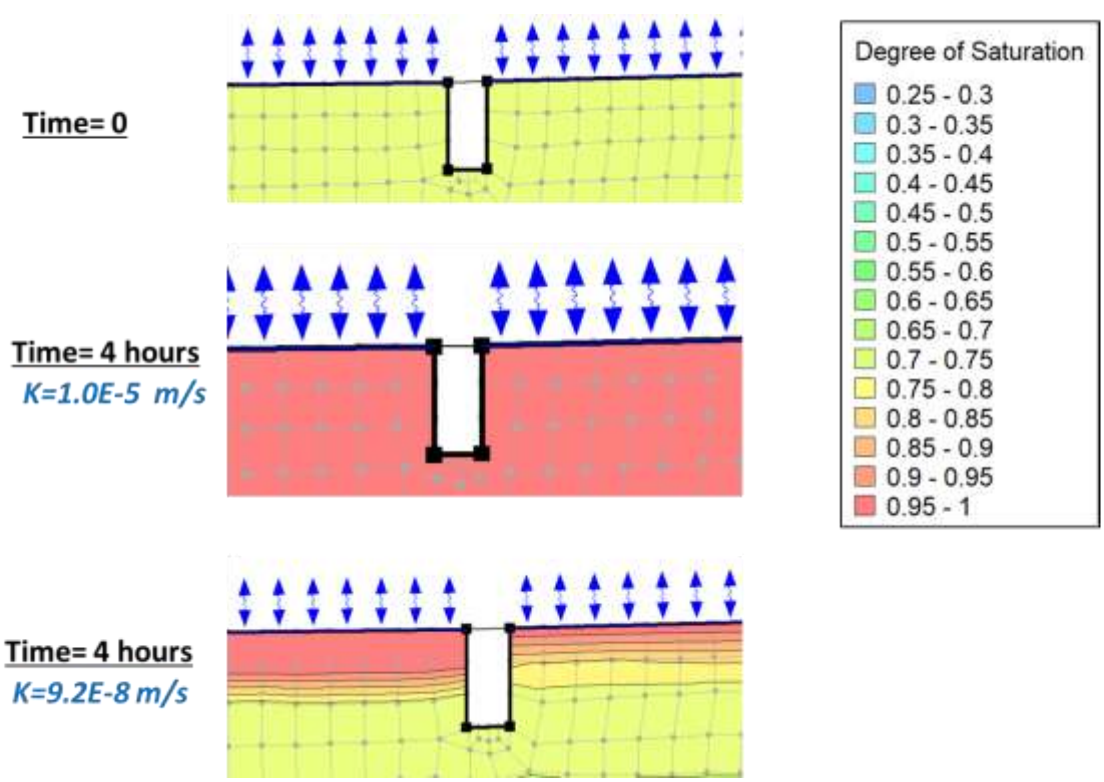


Figure 66

Saturation distribution for the crack-sealed model before (top) and after (middle and bottom) rain event

Effect of the Ground Water Table Depth on Crack Sealing Performance. Six simulation runs were conducted using the sealed FE model considering the following conditions:

- $K_{critical}$ of $2x10^{-6}$ m/s;
- R value of 0.1 in/hour; and
- GWT depths of 2, 4, 10, 20, 40, and 80 m below the pavement surface.

For each run, the saturation was calculated along the three days as shown in Figure 67. For all the GWT depths, the initial saturation remained almost constant along the three days because no rain water entered the pavement since it was assigned a $K_{critical}$. The GWT depth only affected the initial saturation value. The deeper the GWT is, the higher the suction for soils above GWT, and therefore, the lower the initial saturation will be. Since no rain would enter the pavement structure, the GWT level is expected to decrease with time. Therefore, it is concluded that crack sealing could be applied without potential for moisture damage at any GWT depth as long as the permeability of the asphalt mixture satisfies the critical permeability coefficient identified in the previous section. It is worth noting that the initial saturation values (in Figure 67) corresponding to each GWT depth vary significantly depending on the actual SWCC of the original pavement and previous rain events. Therefore, it is highly recommended to select extended dry periods to apply crack sealing. Before application, it is preferred to measure the initial saturation (or moisture content) of the original pavement to ensure that the existing moisture is minimal. Following this recommendation is important as a previous study in Colorado found that pavement failure on a recent SMA overlay was because the milled surface was exposed to about 7.5 in. of precipitation during the months of planning and paving *[66]*. When the SMA overlay was placed, it acted as a moisture sealant where moisture was entrapped leading to asphalt failure.

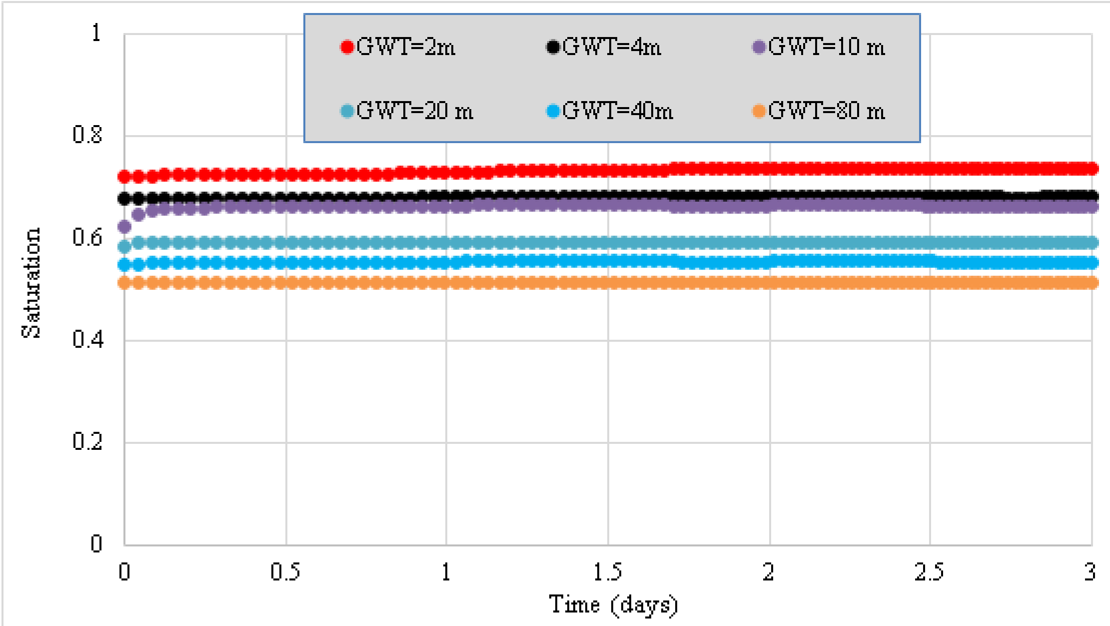


Figure 67
Saturation versus time for the crack-sealed model at different GWT depth

Determination of Moisture Damage Potential for the Unsealed Model. In the previous sections, it was concluded that crack sealing could be applied at different R and GWT without potential for moisture damage as long as the permeability of the asphalt mixture satisfies the critical permeability coefficient. However, to highlight the full benefits of crack sealing it is essential to determine whether the unsealed section would experience moisture damage under different climatic conditions. This was accomplished by running the unsealed model considering the following conditions:

- $K_{critical}$ of $2x10^{-6}$ m/s;
- R values of 0.01, 0.05, and 0.1 in/hr.;
- GWT depths of 2, 4, 10, 20, 40, and 80 m below the pavement surface;
- Air temperature (T) values of 15, 25, and 35°C; and
- Air relative humidity (H) values of 0.3, 0.5, 0.7, and 0.9.

This factorial resulted in a total of 216 runs. For each run, the total time for which the crack-tip was exposed to rain ($t_{critical}$) was calculated as follows:

$$t_{critical} = t_x + t_y + t_z \tag{29}$$

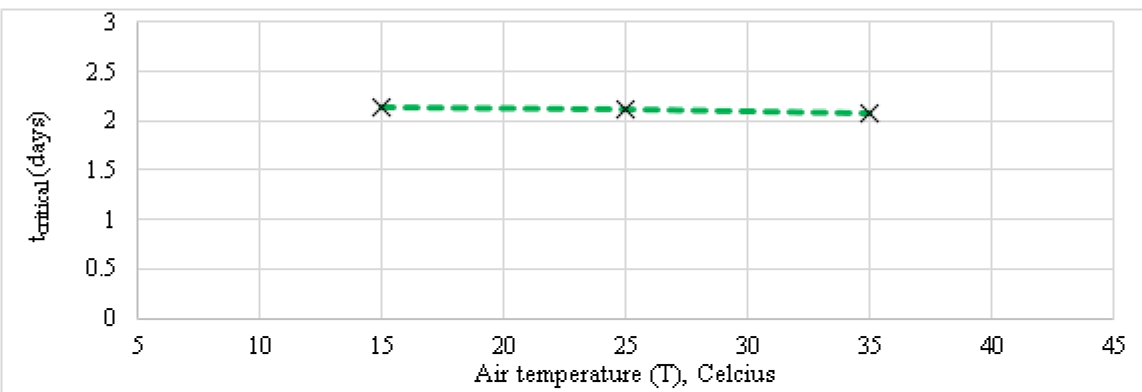
where,

t_x= time during which the saturation increases from the initial value up to 1.0,

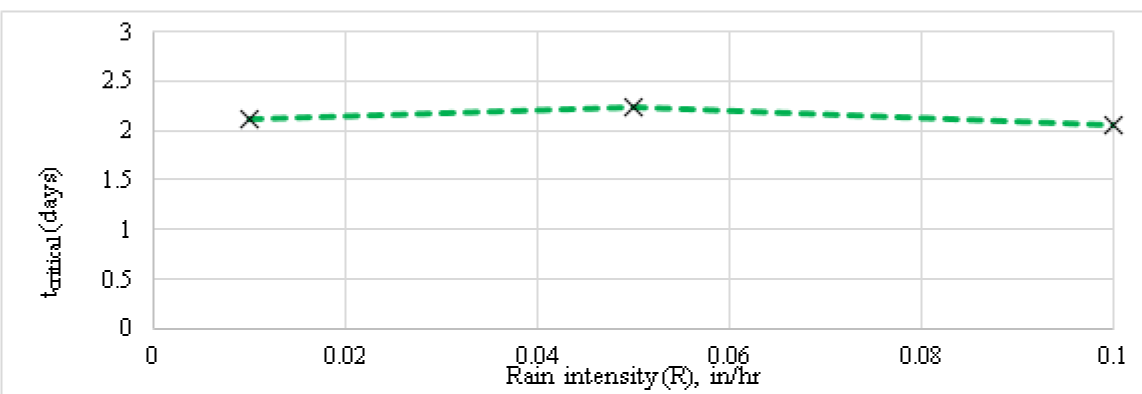
t_y= time during which saturation remains full (1.0), and

t_z= time during which the saturation drops from 1.0 down to the initial value.

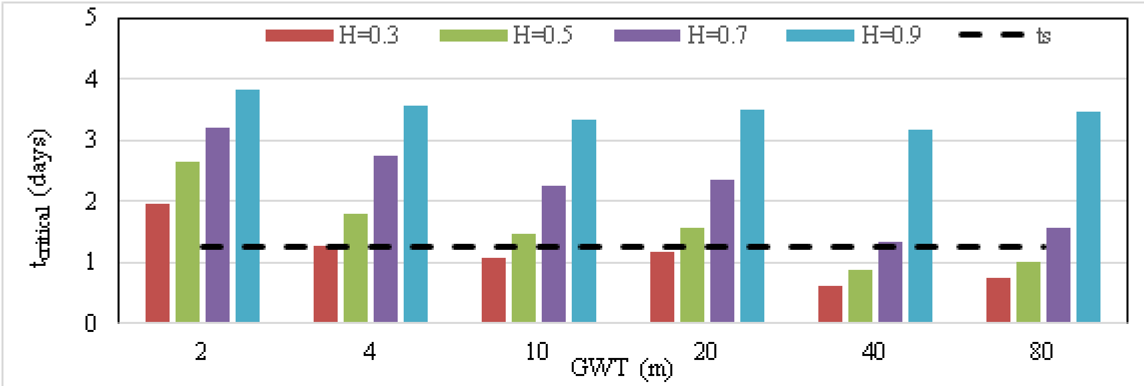
The reported $t_{critical}$ values were grouped by GWT, H, T and R and the average values were calculated for each combination. As shown in Figure 68 (a and b), $t_{critical}$ was almost constant for different values of T and R. On the other hand, $t_{critical}$ varied significantly with different GWT and H, see Figure 68 (c). Based on this figure, the average $t_{critical}$ was less than the t_s (obtained from Lottman test) for conditions such as GWT= 10 m and H=0.3; GWT= 20 m and H=0.3; GWT= 40 m and H= 0.3 or 0.5; and GWT=80 m and H= 0.3 or 0.5. Under these conditions, evaporation occurring at the crack tip of the unsealed section is significant. These conditions accelerate the drainage process of rain water; hence, no moisture damage is expected. However, as shown in Figure 68 (c), under all the other conditions, moisture damage may occur in the unsealed section due to prolonged exposure to water.



(a)



(b)



(c)

Figure 68

$t_{critical}$ for the unsealed section at different (a) air temperature, (b) rain intensity, and (c) GWT and air relative humidity

Regression Analysis and Mathematical Modeling

Correlation between the Finite Element Model Input and Output Parameters. In order to perform a regression analysis, it was necessary to identify which parameters are significant in determining $t_{critical}$ for the unsealed section. This was conducted by constructing a correlation matrix for the FE model input parameters and output results. A summary of this correlation is presented in Table 26. The air relative humidity (H) and GWT showed significant correlations with $t_{critical}$ at the 1% significance level, with H showing the highest correlations (0.797). The temperature (T) and rainfall intensity (R) had very low negative or zero (insignificant) correlations with the finite element model output. Generally, these results agree with the conclusions drawn from Figure 68.

Table 26

Correlation matrix for the FEM input parameters and output results

FE Model Input Parameters	Statistical Measures	FE Model Output ($t_{critical}$)
GWT	Pearson Correlation	-.330**
	Sig. (2-tailed)	.000

FE Model Input Parameters	Statistical Measures	FE Model Output ($t_{critical}$)
T	Pearson Correlation	-.028
	Sig. (2-tailed)	.622
R	Pearson Correlation	-.106
	Sig. (2-tailed)	.059
H	Pearson Correlation	.797**
	Sig. (2-tailed)	.000

**. Correlation is significant at the 0.01 level (2-tailed).

Regression Modeling. An additional 30 runs were conducted for the unsealed section to include a wide range of relative humidity (H) in the regression analysis. In these runs, T and R were kept constant while the GWT and H were varied. Specifically, values of GWT depths were 2, 4, 10, 20, 40, and 80 m, and values of H were 0.1, 0.2, 0.4, 0.6, and 0.8. About 80% of the data were used to fit the non-linear regression model and 20% were used to validate the developed regression model resulting in 318 points for $t_{critical}$ (254 for fitting and 64 for testing). As previously discussed, two independent variables, namely, GWT and H were considered. Furthermore, second and third order of these variables were also considered to develop the non-linear model. The most accurate model from this analysis was as follows:

$$t_{critical} = 1.7621 - 0.0491\ GWT + 0.00044\ GWT^2 + 3.2473\ H^3 \qquad (30)$$

Figure 69 presents the computed $t_{critical}$ from the FE model and using equation (30). The comparison shows that $t_{critical}$ was predicted with an acceptable level of accuracy as indicated by the R^2 and RMSE shown in Figure 69. The proposed regression model was plotted for different GWT and H; see Figure 70. It is noted that the developed model follows the same trends shown in Figure 68(c) based on the finite element analysis.

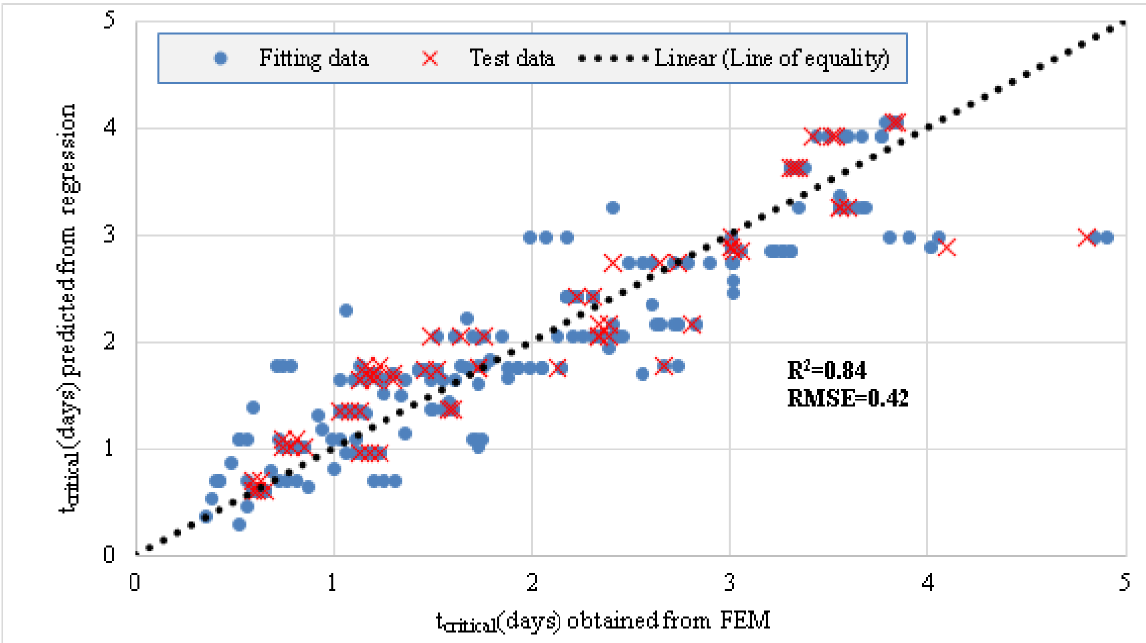


Figure 69

Comparison of FEM output and regression results for $t_{critical}$

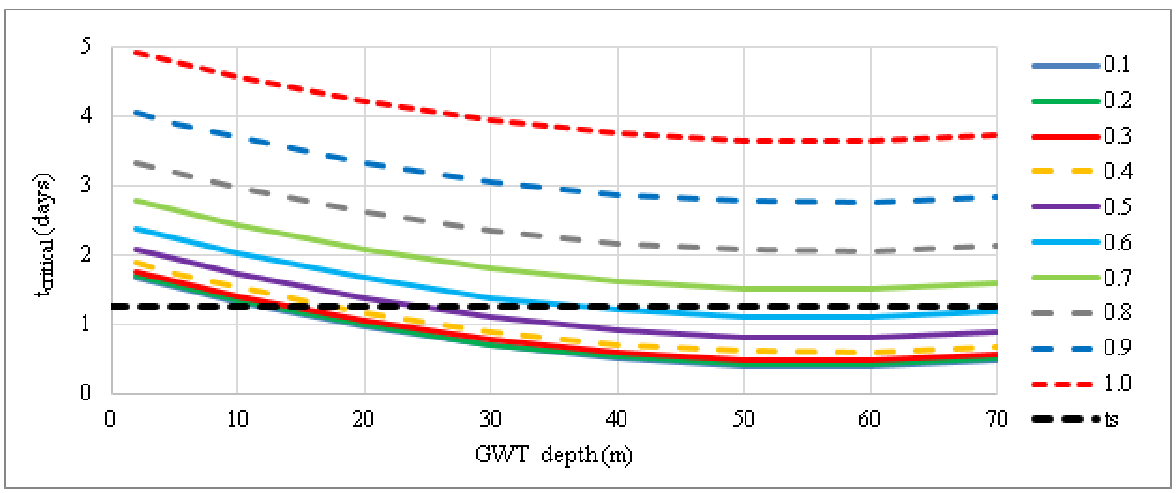


Figure 70

Model prediction of $t_{critical}$ for different GWT and H

Illustrative Application of the Regression Model

The developed regression model can be used in determining if crack sealing should be used to avoid moisture damage in a cracked pavement at a given site as follows:

- **Step 1:** To ensure that $t_{critical}$ for the sealed section will be zero, check that the hydraulic conductivity of the original asphalt mix is less than or equal $2x10^{-6}$ m/s using common field or laboratory devices or using equation (28) knowing the lift thickness, air voids and gradation *[93]*.
- **Step 2:** Use equation (30) or Figure 70 to predict $t_{critical}$ for the unsealed section based on actual data of GWT and average air relative humidity (H) for a given project; and
- **Step 3:** If $t_{critical}$ for the unsealed section is less than 1.3 days (t_s obtained from Lottman test), no moisture damage potential exists in the unsealed section.

These steps were applied to the test section considered in this study as follows:

- **Step 1:** The measured hydraulic conductivity of the existing asphalt was $3.5x10^{-8}$ m/s based on the falling head permeability test; therefore, crack sealing may be used without potential for moisture damage.
- **Step 2:** The GWT depth was 0.6 m, while the average yearly air relative-humidity in Chase is almost 74%. These parameters were used in Equation 30 to predict $t_{critical}$ for the unsealed section (3.0 days).
- **Step 3:** Since $t_{critical}$ exceeds 1.3 days, stripping is expected in the unsealed section. Therefore, crack sealing should be used to avoid moisture damage to the pavement.

To verify these results, the cores extracted during the final site visit were analyzed as shown in Figure 71. Cores 1, 2, and 3 were taken from the unsealed section, while cores 4, 5, and 6 were extracted from the sealed section. Cores 1, 2, and 3 experienced severe moisture damage as indicated by the degradation of the cores as compared to cores 4, 5, and 6. These results agree with the results of the proposed methodology.

(a) Cores from unsealed section

(b) Cores from sealed section

Figure 71
Field cores extracted from the LA 874 road section (Chase, LA) during the final site visit

Evaluate the Effects of Chip seal and Microsurfacing on Moisture Damage

Due to the geographical settings of Louisiana, the pavements are highly susceptible to moisture damage. As microsurfacing seals the pavement surface while chip seal partially seals the surface, it will be logical to suspect that it may trap moisture underneath the pavement causing the moisture to cause progressive damage in the long-term. DOTD performed pavement coring throughout the state where a total number of 1,524 cores were collected from the different districts in Louisiana. To evaluate if moisture damage correlates with the geographical location of the pavement, the number of stripped cores, identified through visual inspection, were quantified for both sections with microsurfacing or chip seal and untreated sections in each district.

The effect of chip seal and microsurfacing on moisture damage was conducted based on the analysis of the cores extracted on the control sections constructed with these treatments. Table 27 summarizes the findings from the core analysis. Comparing the untreated cores with the cores with microsurfacing in Table 27, cores with microsurfacing exhibited higher percentage of stripping in Districts 2, 7, 8, 58, 61, and 62. In addition, Districts 2, 7, 8, and 61 had 10 to 45% more stripped cores than the untreated sections. This indicates that microsurfacing treatments seem to contribute to moisture damage.

Table 27
Summary of the cores extracted from different districts in Louisiana

District	Total Cores Obtained	Untreated Sections		Sections with Chip Seal		Sections with Microsurfacing	
		Number of Cores	Cores with Stripping (%)	Number of Cores	Cores with Stripping (%)	Number of Cores	Cores with Stripping (%)
2	95	91	4 (4)	0	0 (N/A)	4	2 (50)
3	252	238	54 (23)	12	5 (42)	2	0 (0)
4	219	150	24 (16)	65	6 (9)	4	0 (0)
5	118	71	25 (35)	44	17 (39)	3	0 (0)
7	133	98	49 (50)	25	11 (44)	10	6 (60)
8	154	130	40 (31)	18	6 (33)	6	3 (50)
58	144	65	15 (23)	68	29 (43)	11	3 (27)
61	201	171	48 (28)	23	7 (30)	7	3 (43)
62	208	142	13 (9)	56	7 (13)	10	1 (10)
Sum	**1,524**	**1,156**	**272**	**311**	**88**	**57**	**18**

Comparing the untreated cores with the cores with chip seal in Table 27, cores with chip seal exhibited about the same percentage of stripped cores in all the districts except for Districts 3 and 58. Based on these results, it is concluded that chip seal appears to have minimal or negligible contribution to moisture damage in Louisiana. This could be due to the fact that chip seal does not completely seal the surface, and therefore no moisture entrapment occurs beneath this treatment.

Another key observation drawn from Table 27 is that moisture damage in pavements is significantly influenced by their geographic location regardless of the applied treatment. For example, District 7, which is generally characterized by its shallow groundwater table had the highest percentage of stripped cores for both treated and untreated sections. This observation suggests that shallow ground water could contribute to moisture damage in AC pavements in general (treated or untreated) due to moisture entrapment under the AC layer. This finding agrees with previous studies reporting that moisture may get entrapped beneath AC overlays *[61, 66]*.

A detailed forensic analysis was conducted on (a) six moisture-damaged sections with chip seal and (b) four moisture-damaged sections with microsurfacing to evaluate the contributing factors to moisture damage in these sections.

Moisture-Damaged Sections with Chip Seal

Section 154-03. The road is located in Union Parish of District 5. It received a major rehabilitation in 1981 and carries an ADT of 780. The section had a length of 6.31 mile and the pavement structure consists of a 6.5 in. AC layer and 12 in. red sand base layer on top of a brown clayey sand subgrade. A chip seal treatment was applied in 2008. At the location of the core, the PCI was 88.7 and the average PCI along the section was 77.7. The section receives about 57 in. of annual rainfall and numerous stagnant water bodies along with an open channel were observed within a close proximity of the road, see Figure 72(a). The abundance of water in the proximity of the pavement structure may be a contributing factor to moisture damage.

Section 188-03. The road is located in Allen Parish of District 7. It received a major rehabilitation in 1998 and carries an ADT of 920. The section had a length of 13.54 mile and the pavement structure consists of a 7.5 in. AC layer and 6.5 in. red sand with small aggregate base layer on top of a brown sand subgrade. A chip seal maintenance was constructed in 2008. At the location of the core, the PCI was 84.2 and the average PCI along the section was 91.1. The section receives about 62 in. of annual rainfall and the road is located within a 1-mile radius of two large water bodies (Sweet Lake and Willow Lake). The close proximity to water bodies as well as the expected shallow GWT in this area may have contributed to moisture damage underneath the pavement; see Figure 72(b).

Section 042-03. The road is located in Sabine Parish of District 8. It received a major rehabilitation in 1981 and carries an ADT of 740. The section has a length of 10.68 mile and the pavement structure consists of a 7 in. AC layer and 26 in. red sand base layer on top of a tan sand subgrade. A chip seal maintenance was conducted in 2008. At the location of the core, the PCI was 84.4 and the average PCI along the section was 77.4. The section receives about 54 in. of annual rainfall. No significant water bodies were found near the section although the extracted core was severely stripped as only about 2 in. out of the 7 in. of AC could be recovered from the core, see Figure 72(c).

Section 039-01. The road is located in Lasalle Parish of District 58. It received a major rehabilitation in 1999 and carries an ADT of 760. The section had a length of 4.74 mile and the pavement structure consists of a 3.5 in. AC layer and 11 in. cement stabilized sand shell base on top of a sand subgrade. A chip seal maintenance was conducted in 2008. At the location of the core, the PCI was 89.5 and the average PCI along the section was 82.9. The section receives about 58 in. of annual rainfall. The section had a good drainage condition and no significant waterbody was observed nearby except for Little Creek, see Figure 72(d).

Section 259-01. The road is located in East Feliciana Parish of District 61. It received a major rehabilitation in 1986 and carries an ADT of 1,600. The section had a length of 13.31 mile and the pavement structure consists of a 13 in. AC layer on top of a light brown sandy clay subgrade. A chip seal maintenance was conducted in 2008. At the location of the core, the PCI was 91.3 and the average PCI along the section was 83.7. The section receives about 62 in. of annual rainfall and most part of the section passes alongside the Amite River, which indicates that the section may have exhibited severe stripping due to shallow groundwater table, see Figure 72(e).

Section 274-01. The road is located in Washington Parish of District 62. It received a major rehabilitation in 1985 and carries an ADT of 4,900. The section had a length of 10.25 mile and the pavement structure consists of a 5 in. AC layer and 7 in. stabilized granular base on top of a clay subgrade. A chip seal maintenance was conducted in 2008. At the location of the core, the PCI was 71.5 and the average PCI along the section was 76.8. The section receives about 62 in. of annual rainfall and numerous water bodies around the section along with an open channel West Fork Burch Creek were found within a close proximity of the road section. The abundance of water bodies may have significantly contributed to moisture damage in the pavement, see Figure 72(f).

(a) 154-03

(b) 188-03

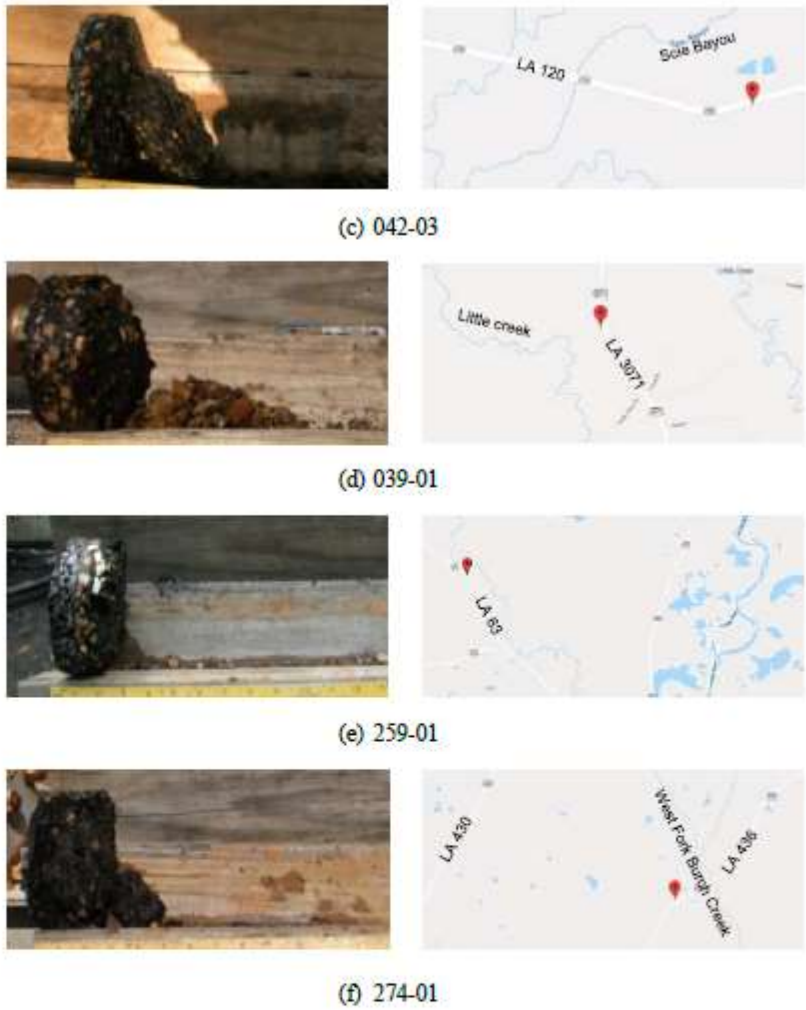


Figure 72
Moisture damaged sections with chip seal

Moisture Damaged Sections with Microsurfacing

Section 146-01. The road is located in Avoyelles Parish of District 8. It received a major rehabilitation in 1987 and carries an ADT of 3,500. The section had a length of 12.29 mile and the pavement structure consists of a 15 in. AC layer on top of a brown clay subgrade. A microsurfacing maintenance was conducted in 2006. At the location of the core, the PCI was 91.7 and the average PCI along the section was 91.8. The section receives about 59 in. of annual rainfall and most part of the section passes alongside a stagnant waterbody within a 300 ft. proximity, which may have significantly contributed to moisture damage underneath the pavement; see Figure73(a).

Section 193-01. The road is located in Cameron Parish of District 7. It received a major rehabilitation in 1991 and carries an ADT of 1,620. The section had a length of 13.38 mile and the pavement structure consists of an 8.5 in. AC and a 9.5 in. of crushed gravel with sand base on top of a clay subgrade. A microsurfacing maintenance was conducted in 2010. At the location of the core, the PCI was 91.4 and the average PCI along the section was 86.4. The section receives about 62 in. of annual rainfall. The core location is within half a mile radius of the Bayou Serpent River, which may indicate a shallow groundwater table; see Figure 73(b).

Section 193-02. The road is located in Cameron Parish of District 7. It received a major rehabilitation in 1990 and carries an ADT of 2,600. The section had a length of 14.28 mile and the pavement structure consists of a 10 in. AC and a 15 in. of sand base on top of a fat clay subgrade. A microsurfacing maintenance was conducted in 2010. At the location of the core, the PCI was 85.9 and the average PCI along the section was 90.7. The section receives about 62 in. of annual precipitation. However, no significant water bodies were found near the section; see Figure 73(c).

Section 374-03. The road is located in Avoyelles Parish of District 8. It received a major rehabilitation in 1966 and carries an ADT of 510. The section had a length of 18.42 mile and the pavement structure consists of a 7 in. AC layer on top of a red silty sand subgrade. A microsurfacing maintenance was conducted in 2003. At the location of the core, the PCI was 81.5 and the average PCI along the section was 88.4. The section receives about 57 in. of annual precipitation. Numerous small water bodies were found near the section as it is located very close to the Red River; see Figure 73(d).

(a) 146-01

Figure 73
Moisture damaged sections with microsurfacing

Closing Remarks

The detailed analysis of the 10 aforementioned moisture-damaged sections revealed that despite having a good to excellent PCI rating, these sections have significant moisture damage underneath the pavement surface. Compared to the age of these pavements, chip seal and microsurfacing treatments were applied only recently. Results did not show that chip seal is a primary contributor to moisture damage in these pavements since the applied emulsion does not entirely seal the pavement surface. On the other hand and considering that microsurfacing-treated sections exhibited higher percentage of moisture damage as compared to the untreated sections in most of the districts, a concern exists that microsurfacing may contribute to moisture damage in asphalt pavements. The reduction of water evaporating from the pavement surface due to the application of microsurfacing may be the reason for the observed trends. Therefore, an in-depth assessment of the effects of microsurfacing on moisture damage in asphalt pavements should be conducted especially in areas with shallow groundwater table considering factors such as precipitation, evaporation, and permeability of the pavement layers.

Development of an Enhanced Decision Making Tool

Introduction

The objective of this task was to combine the results of the previous tasks into an enhanced decision-making tool that can be used to select the most optimum maintenance treatment (do nothing, crack sealing, chip seal, or microsurfacing) based on the specific road conditions. In the selection process, the following three key criteria were considered:

- Surface distresses in the existing overlay, such as, surface cracks, rutting, and roughness;
- Potential subsurface moisture damage as a result of maintenance treatment application; and
- Cost effectiveness of the applied maintenance treatment.

Furthermore, the developed tool could be used to determine the optimal timing, in terms of RCI or PCI, of the selected maintenance treatment.

Developed Tool Framework

In order to ensure that the tool is time-efficient and easy to use so that it can be adopted by PMS engineers, the tool was developed using macros in Microsoft Excel. Once the tool is started, the Master Sheet appears, which controls all the worksheets in this tool. The Master Sheet consists of seven key buttons including seven sequential steps that need to be completed in the presented order; and one final button for saving changes and closing the tool. Pressing the first button (Step 1 button), will transfer the user from the Master Sheet to a new worksheet, Step 1 worksheet, that provide general instructions. Next, the user should press the “Return to Master Sheet” button at the end of the worksheet to return to the Master Sheet and complete Steps 2 to 7 similarly. It is worth noting that Step 1 is related to the tool instructions, Steps 2 to 4 are related to the design inputs that need to be filled, and Steps 5 to 7 are related to the tool output. The following subsection provides additional details of the seven steps in the developed tool.

Step 1: Go to Instructions. This button transfers the user from the Master Sheet to the Step 1 worksheet, which provides instructions to the user to read before using the selection tool.

Step 2: Enter General Data Applicable to Site. This button transfers the user from the Master Sheet to Step 2 worksheet. This worksheet starts with an illustration, shown in Figure 74, that presents the definition of the parameters that are included in this tool. Specifically, Year A is the year at which the existing AC overlay was applied, Year B is the base or current year at which the tool is used, and Year C is the year at which the maintenance treatment is planned to be applied. It is worth noting that Years B and C could be the same. Minimum and maximum values are provided in this worksheet for each year to guide the user in the selection. To avoid errors, the spreadsheet is designed such that Year A should precede Years B and C, and Year C should follow or be the same as Year B. Furthermore, in this worksheet, the user should select the district number from a provided list of districts in Louisiana. For convenience, a table is provided showing district numbers and corresponding district names. After that, the user should input the expected ADT when the maintenance treatment is applied; i.e., at year C. The ADT input should be less than 11,100 vehicles per day. In addition, the user should select the discount rate between 3% and 6%.

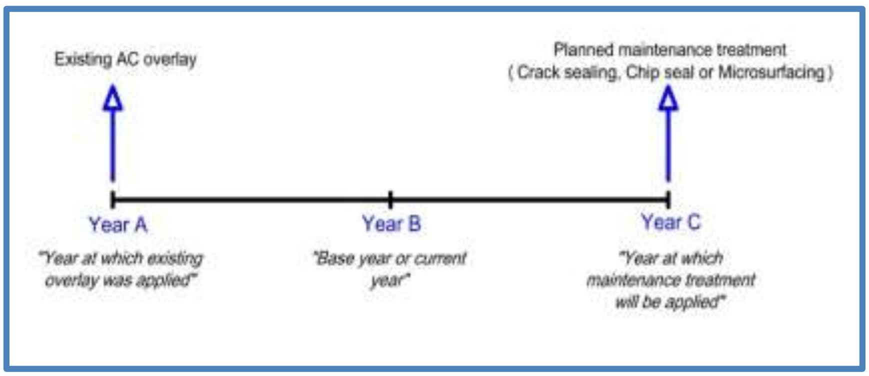


Figure 74
Illustration of years' definitions in the input data

Step 3: Enter Maintenance Treatments Unit Costs. The next step transfers the user from the Master Sheet to Step 3 worksheet. In this worksheet, the user should input the unit cost (in $/lane-mile) for crack sealing, chip seal, and microsurfacing at Year C. Since these values vary significantly from one year to another, the spreadsheet does not provide maximum and minimum values for these inputs. Instead, the maximum and minimum values are set at 9999999 and 0, respectively. For the user's convenience, typical unit costs of each maintenance treatment are provided at specific years. These typical values are based on actual costs of field projects in Louisiana. For example, it is provided that the unit cost of crack sealing in 2017 was $10,296/lane-mile.

Step 4: Enter Existing AC Overlay Data. The next step transfers the user from the Master Sheet to Step 4 worksheet. This worksheet requires the user to input the unit cost (in $/lane-mile) of the existing AC overlay when applied (at year A). As the case with maintenance treatments, the maximum and minimum values are set 9999999 and 0, respectively, and typical AC overlay unit costs are provided at different years. Yet, the user is expected to have access to the unit cost from historical records. The user should also input the thickness of the existing overlay (in inches) between 1 and 6 in. This value should encompass only the thickness of the existing AC overlay, which was applied at Year A not the total AC thickness. Next, the user should select the type of pavement from a numerical list of 1 and 2, where 1 refers to flexible pavement and 2 refers to composite pavement. A challenging key input required in this category is the hydraulic conductivity or water permeability (in m/s) of the existing AC overlay. Ideally, a core should be taken from the existing AC overlay and tested in the laboratory using the quick Falling Head Permeability Test, shown in Figure 24. Otherwise, the user could use the typical values provided in the spreadsheet for dense graded asphalt mixes (9.20×10^{-8} to 1.00×10^{-5} m/s). Furthermore, the user should input the PCI, RCI, RTI and RFI of the existing overlay at Year C, which could be simply obtained from the PMS database.

Step 5: Go to Results of Surface Distresses Analysis. The next step transfers the user from the Master Sheet to Step 5 worksheet. This worksheet is shown in Figure 75 and selects the best maintenance treatment that addresses the road existing surface distresses, i.e. rutting, roughness and cracking without considering the cost-effectiveness of this treatment or its stripping potential. This selection is solely based on the RCI, RTI, and RFI of the existing overlay at Year C, which are entered by the user in Step 4.

Step 6: Go to Subsurface Moisture Damage Results. The next step transfers the user from the Master Sheet to Step 6 worksheet. This worksheet is shown in Figure 76 and presents the results related to the potential moisture damage for each maintenance treatment. For chip seal and microsurfacing, the probability of stripping is presented based on the geographical location of the district provided by the user in Step 2. It is recommended to avoid any maintenance treatment when its stripping probability exceeds 50%. As shown in Figure 76, the worksheet also predicts whether stripping will occur after crack sealing assuming that crack sealing is applied during an extended dry weather period. It is worth noting that the prediction depends on the hydraulic conductivity entered by the user in Step 4.

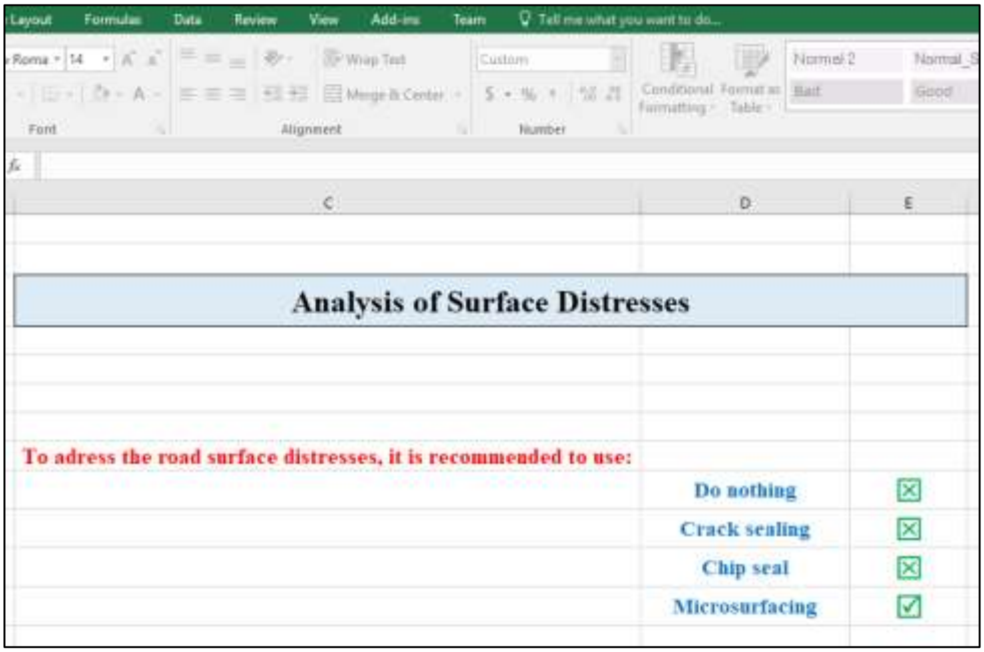


Figure 75
Output worksheet in Step 5

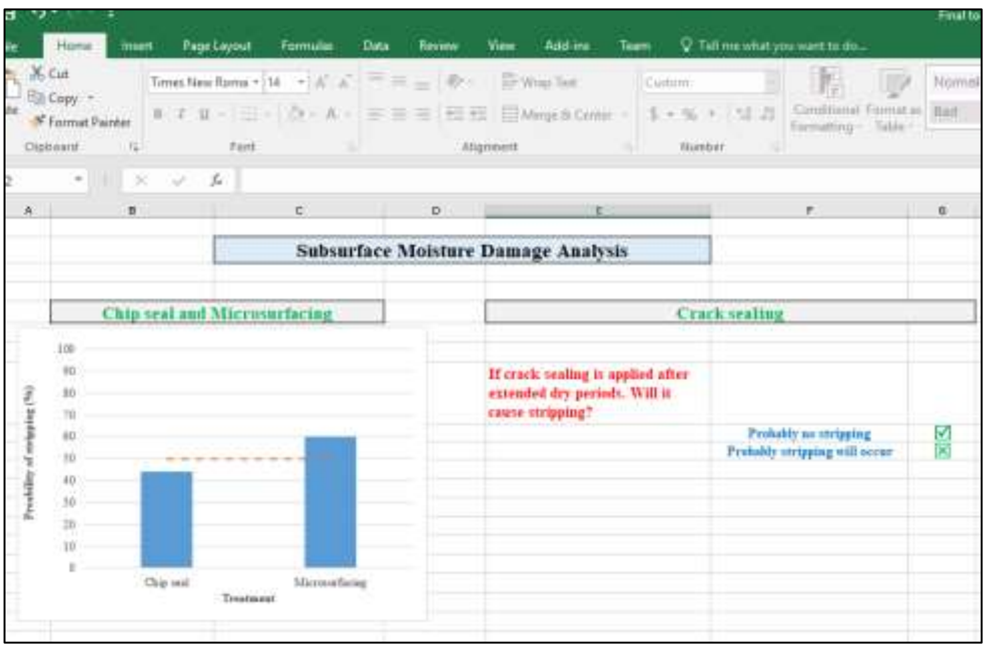


Figure 76
Output worksheet in Step 6

Step 7: Go to Performance and Cost Benefit Results. The next step transfers the user from the Master Sheet to Step 7 worksheet. This worksheet is shown in Figure 77 and presents the calculated ΔPSL, EAC, B/C, and CE for each maintenance treatment. These computations are based on the input data entered by the user, specifically the RCI and PCI of the existing AC overlay. While ΔPSL is based only on the treatment performance without considering the relevant costs, EAC, B/C, and CE reflect the treatment cost effectiveness. The treatment with the lowest EAC, highest B/C, and highest CE is the most cost effective treatment. Any negative values in this worksheet would mean that the relevant treatment is not cost-effective; therefore, it should be avoided.

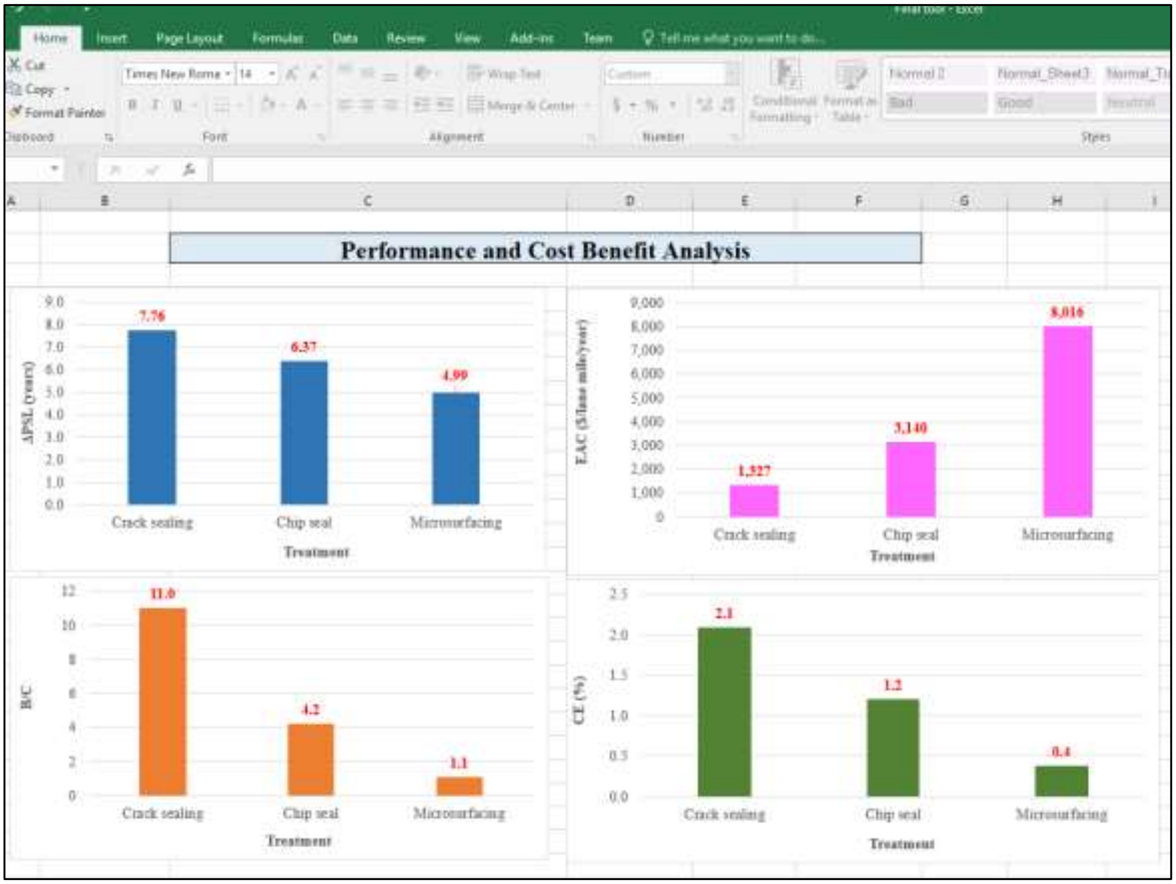


Figure 77
Output worksheet in Step 7

It is worth noting that the user should consider the results of the three worksheets in Steps 5 to 7 simultaneously before making a final decision regarding the most appropriate maintenance treatment. For example, crack sealing may be the most cost effective treatment for a specific project because of its relatively low cost, but it might not be suitable if the prevalent distress in the existing overlay is rutting or roughness or if crack sealing has high stripping potential.

In addition to its ability to select the most appropriate treatment, this tool could be used to determine the optimal timing of the selected maintenance treatment. This could be achieved by changing the pre-treatment pavement conditions (RCI in case of crack sealing and PCI in case of chip seal and microsurfacing) in Step 4 and tracking the resulting EAC, B/C, and CE in Step 7. The RCI or PCI that results in the lowest EAC and highest B/C or CE, which coincides with the optimal timing of the selected maintenance treatment, is also provided in Step 7.

CONCLUSIONS

The objective of this study was twofold. First, this project quantified the benefits of using crack sealing, chip seal, and microsurfacing with respect to their ability to provide immediate and long-term benefits. Based on this evaluation, the research team developed regression models that predict crack sealing benefits; in terms of extension in pavement service life, based on the project conditions. Second, this project evaluated the potential moisture damage in pavements treated with crack sealing, chip seal, and microsurfacing. Based on this evaluation, the research team developed a regression model that determines whether crack sealing should be used to avoid moisture damage in a cracked pavement at a given site based on the ground water table depth and air relative-humidity. Furthermore, this project assessed the optimal application timing of crack sealing, chip seal, and microsurfacing by evaluating the cost effectiveness of these treatments using common economic measures. Based on the results of the study and the conducted cost analysis, researchers drew the following key conclusions.

DOTD State-of-the-Practice

- Chip seal and crack sealing are the two most common preventive maintenance treatments used in Louisiana, whereas ultrathin overlay and microsurfacing are occasionally used. Neither fog seal nor slurry seal are used in Louisiana for pavement maintenance.
- In 2016, the average annual budget spent per district on crack sealing, chip seal, and microsurfacing were $90,333, $1,700,000, and $1,047,667, respectively.
- All the maintenance treatments, except crack sealing, are applied in Louisiana based on pavement conditions and visual inspection, whereas, crack sealing is usually applied solely based on visual inspection.

Laboratory Results of Crack Sealant Materials

- The two most common sealant materials in Louisiana are hot-poured rubberized asphalt (Crafco) and cold-applied asphalt emulsion (CRS-2).
- The rubberized asphalt sealant used in Louisiana (Type II) conforms to the ASTM D 6690-15 specifications based on the results of the cone penetration test, resilience test, softening point test and bonding test.
- Based on the Performance Grading (PG) test results, the higher temperature grades for

the emulsified crack sealant residue and the rubberized asphalt binder were PG 58 and 88, respectively. The low temperature grade for the emulsion residue was PG -28. The low temperature grade for the rubberized asphalt binder could not be determined since the sample was too soft and therefore, could not be tested using the BBR.

Field Performance of Crack Sealing

- Crack sealing resulted in a significant Performance Jump in RCI with a mean value of 7.4 ± 7.3, whereas no significant Performance Jump in RFI was observed.
- For all the evaluated control sections with a few exceptions, the sealed segment experienced an average increase in PSL of two years more than the unsealed segment.
- In comparison with original pavement, crack sealing did not extend PSL when added to pavements with RCI^{-} above 90. When RCI^{-} was less than 90, crack sealing extended the PSL by 5.6 and 3.2 years for flexible and composite pavements, respectively.
- The developed regression models predicted ΔPSL with an acceptable level of accuracy based on R^2 and RMSE. The pre-treatment RCI^{-} was the most important variable in predicting ΔPSL.
- The proposed models were accurate in predicting whether crack sealing will increase PSL as well as the magnitude of the improvement.

Field Performance of Chip Seal and Microsurfacing

- Chip seal is effective in addressing pavement random cracking. Furthermore, it slightly improves pavement roughness.
- Microsurfacing is effective in addressing most of the pavement distresses, in particular, rutting and roughness.
- Chip seal and microsurfacing did not significantly extend PSL when added to pavements with pre-treatment PCI^{-} above 90.
- When applied to pavements with $PCI^{-}<90$, chip seal extended the service life of the pavements by 6.4 to 10.5 years, while microsurfacing extended the service life of the pavements by 4.9 to 8.8 years.

Cost Benefit Analysis

- The optimal timing of crack sealing is when the RCI of the AC overlay drops to any conditions between 81 and 84.
- The optimal timing of chip seal is when the PCI of the AC overlay drops to any conditions between 50 and 77.
- The optimal timing of microsurfacing is when the PCI of the AC overlay drops to any conditions between 50 and 84.

Effect of Crack Sealing on Moisture Damage

- Crack sealing could be applied under common rain intensities in Louisiana and for any ground water table depth without the potential for moisture damage in asphalt pavement due to moisture entrapment if the original pavement is relatively impermeable (water permeability is less than $2\text{x}10^{-6}$ m/s).
- Crack sealing should be applied after an extended dry period to ensure that the existing moisture is minimal.
- Unsealed cracks in regions with relatively low air relative humidity and deep ground water table are not expected to experience moisture damage (stripping) due to the accelerated drainage by evaporation.

Effect of Chip Seal and Microsurfacing on Moisture Damage

- Chip seal treatments seem to have minimal or negligible contribution to moisture damage in Louisiana. This could be due to that the applied emulsion does not entirely seal the surface, and therefore no moisture entrapment occurs beneath this treatment.
- Microsurfacing seems to contribute to moisture damage in Louisiana probably due to the reduction of water evaporating from the pavement surface due to the application of microsurfacing.
- Moisture damage in AC pavement is significantly influenced by its geographic location regardless of the treatment. For instance, shallow ground water could contribute to moisture damage in AC pavement (treated or untreated) due to moisture entrapment

under the AC layer itself.

Development of an Enhanced Decision Making Tool

Based on the aforementioned conclusions, the research team developed a user-friendly tool in the form of a spreadsheet that could be used by state agencies during planning of maintenance activities. This tool requires the user to input key project conditions such as the average daily traffic volume, thickness of the existing asphalt pavement, pre-treatment pavement condition, etc. For each input, typical ranges and recommended values are provided to guide the user in selecting the design values. Based on the provided input values, the tool would select the most cost-effective maintenance treatment (crack sealing, chip seal, microsurfacing or do nothing) that addresses existing surface distresses without causing moisture damage.

RECOMMENDATIONS

Based on the findings of this project, it is recommended to use the developed tool before selecting a maintenance treatment. For a specific project, this tool will predict the most cost-effective maintenance treatment (crack sealing, chip seal, microsurfacing or do nothing) that addresses existing surface distresses without causing moisture damage. The tool will also provide the optimal timing of the selected maintenance treatment. Future activities should also consider the following important research needs:

- An in-depth assessment of the effects of microsurfacing on moisture damage in asphalt pavements should be conducted especially in areas with shallow groundwater table;
- Crack sealing should be incorporated in the decision matrix currently used by PMS in selecting treatment methods;
- The use of crack sealing should be promoted in the State to take advantage of its high cost-effectiveness especially in sections in relatively good conditions as a preventive maintenance measure.
- Crack sealing should be incorporated in the State Standard Specifications for Roads and Bridges.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AAPX	Precipitation Load Factor
AC	Asphalt Concrete
ADT	Average Daily Traffic
ADTX	Traffic Load Factor
ANOVA	Analysis of Variance
APG	Average Performance Gain
ARAN	Automatic Road Analyzer
B/C	Benefit Cost
BBR	Bending Beam Rheometer
CE	Cost Effectiveness
DOT	Department of Transportation
DOTD	Louisiana Department of Transportation
DRR	Deterioration Rate Reduction
DSR	Dynamic Shear Rheometer
EAC	Equivalent Annual Cost
EF	Effectiveness
EUAC	Equivalent Uniform Annual Cost
FEM	Finite Element Model
FHWA	Federal Highway Admiration
GPR	Ground Penetrating Radar
GWT	Ground Water Table
H	Air Relative Humidity
HAL	Hot Air Lance
HMA	Hot Mix Asphalt
IRI	International Roughness Index
K_{sat}	Saturated Hydraulic Conductivity
LCCA	Life-Cycle Cost Analysis
LCI	Land Climate Interaction
LTPP	Long-Term Pavement Performance
LTRC	Louisiana Transportation Research Center
NCHRP	National Cooperative Highway Research Program
NMAS	Nominal Maximum Aggregate Size
NPV	Net Present Value
PAV	Pressure Aging Vessel
PCI	Pavement Condition Index or Composite Index
PCI^-	Pre-Treatment Pavement Condition Index

AAPX	Precipitation Load Factor
PCR	Pavement Condition Rating
PG	Performance Grade
PJ	Performance Jump
PMS	Pavement Management System
PSL	Pavement Service Life
PSL*	Increase in PSL, compared to a nearby untreated section
QA	Quality Assurance
R	Rain Intensity
R^2	Coefficient of determination
RCI	Random Cracking Index
RCI^-	Pre-Treatment Random Cracking Index
RFI	Roughness Index
RMSE	Root Mean Square Error
RTFO	Rolling Thin Film Oven
RTI	Rutting Index
SG	Sealant Grade
SHRP	Strategic Highway Research Program
SMA	Stone Matrix Asphalt
SWCC	Soil Water Characteristics Curve
T	Air Temperature
TNB	Treatment Net Benefits
TSR	Tensile Strength Ratio
VMC	Volumetric Moisture Content
ΔPSL	Increase in PSL, compared to the same section before treatment

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APPENDIX A: QUESTIONNAIRE

LTRC Research Questionnaire

Improving the use of crack sealing to asphalt pavement in Louisiana

The Louisiana Transportation Research Center (LTRC) has started a study to evaluate the use of pavement preservation techniques by districts, parishes, and cities in Louisiana. Please complete the questionnaire below and email it to Mostafa Elseifi, Professor, Louisiana State University, at elseifi@lsu.edu. Should you have any questions regarding this questionnaire, please call Mostafa Elseifi at (225) 578-4821.

Please return the questionnaire by November 1, 2016. We appreciate your timely response.

Name:
Title:
District/City/Parish:
Phone Number:
E-mail:

QUESTION 1: ***Which of the following pavement preservation methods do you currently use in your district/city/parish (Highlight all methods that you use)?***

Treatments	***Use in your district/city/parish (Yes/No)***
Crack sealants	
Fog seal	
Slurry seal	
Micro-surfacing	
Ultrathin bonded wearing course	
Ultra-thin overlay (less than 2 in.)	
Chip seal	
Others (please clarify)	

QUESTION 2: ***What is the overall budget spent in 2014 or 2015 on the following treatment methods?***

Treatments	***Annual Budget ($/year)***
Crack sealants	

Fog seal	
Slurry seal	
Micro-surfacing	
Ultrathin bonded wearing course	
Ultra-thin overlay (less than 2 in.)	
Chip seal	
Others (please clarify)	

QUESTION 3: ***Do you keep record of the roads (construction files) in which the following treatment methods are used?***

Treatments	***Yes/No***
Crack sealants	
Fog seal	
Slurry seal	
Micro-surfacing	
Ultrathin bonded wearing course	
Ultra-thin overlay (less than 2 in.)	
Chip seal	
Others (please clarify)	

QUESTION 4: ***Do you select the roads to be treated based on pavement conditions (PMS data) through a pre-set schedule, visual inspection?***

Treatments	***PMS***	***Pre-Set Schedule***	***Visual Inspection***
Crack sealants			
Fog seal			
Slurry seal			
Micro-surfacing			
Ultrathin bonded wearing course			
Ultra-thin overlay (less than 2 in.)			
Chip seal			
Others (please clarify)			

QUESTION 5: ***Do you perform the following treatment methods in-house or through external contracts?***

Treatments	*In-House*	*External Contracts*
Crack sealants		
Fog seal		
Slurry seal		
Micro-surfacing		
Ultrathin bonded wearing course		
Ultra-thin overlay (less than 2 in.)		
Chip seal		
Others (please clarify)		

QUESTION 6: ***Do you perform any laboratory testing for acceptance of crack sealant materials?***

- Yes (Please Clarify):
- No

QUESTION 7: ***Do you perform any QA for acceptance of installed treatment methods?***

Treatments	*QA Activities*	*Please clarify*
Crack sealants		
Fog seal		
Slurry seal		
Micro-surfacing		
Ultrathin bonded wearing course		
Ultra-thin overlay (less than 2 in.)		
Chip seal		
Others (please clarify)		

QUESTION 8: **We are planning to conduct a field experiment in which a district/city/parish will apply pre-selected pavement preservation treatment methods in**

a road segment and LSU/LTRC will monitor their performance and cost-effectiveness. The installation will take place during the next construction season. Would you be interested to participate?

Please note that there is no extra cost to be incurred by the district/city/parish by participating in the field experiment. A district/city/parish will construct a road section as they usually do using one or more preventive maintenance methods. The only difference is that LSU/LTRC will know of this section in advance, we will survey the section before construction, and we will monitor its performance after construction.

- Yes
- No

Thanks!

APPENDIX B: SAMPLE CALCULATION OF B/C

Given information:

- Control section: 001-03
- Log mile beginning: 6.2
- Log mile end: 6.3
- Treatment type: crack sealing
- Net present value of crack sealing: $10,296/ mile
- Net present value of existing overlay: $375,855/mile
- PSL of existing AC overlay (without crack sealing) = 12.19 years
- ΔPSL due to crack sealing = 2.79 years
- Total PSL of existing overlay after crack sealing = 12.19+2.79 = 14.98 years
- Interest rate = 6%

Calculations:

$$\mathrm{EUAC}_{\text{do nothing}} = 375{,}855 \times \left[\frac{0.06(1.06)^{12.19}}{(1.06)^{12.19} - 1}\right] = \$44{,}348$$

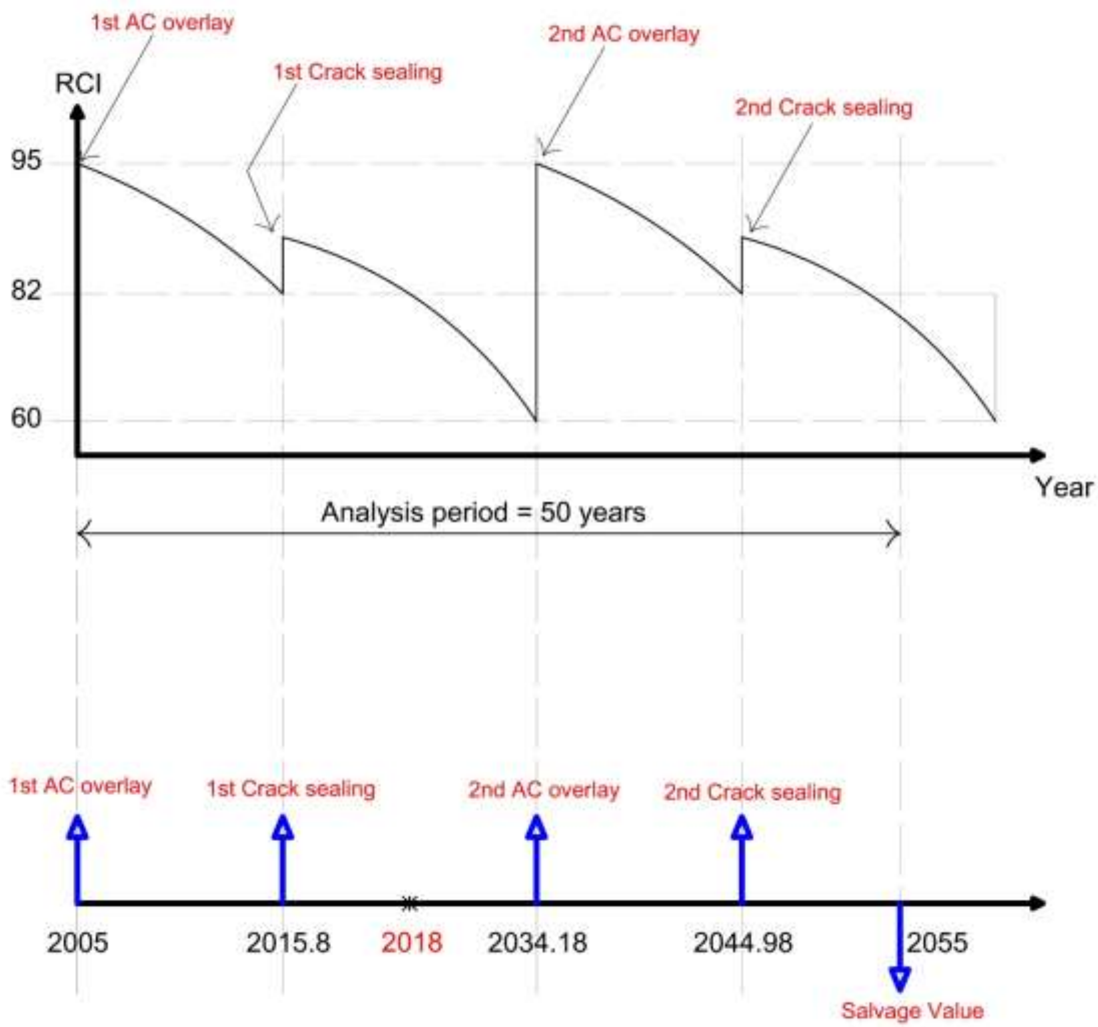
$$\mathrm{EUAC}_{\mathrm{PVC}} = 10{,}296 \times \left[\frac{0.06(1.06)^{14.98}}{(1.06)^{14.98} - 1}\right] = \$1{,}061$$

$$\mathrm{EUAC}_{\text{treatment}} = (375{,}855 + 10{,}296) \times \left[\frac{0.06(1.06)^{14.98}}{(1.06)^{14.98} - 1}\right] = \$39{,}792$$

$$\frac{\mathrm{B}}{\mathrm{C}} = \frac{44{,}348 - 39{,}792}{1{,}061} = 4.29$$

APPENDIX C: SAMPLE CALCULATION OF TOTAL NPV FOR THE CASE STUDY

Illustration of the total NPV calculation



Preliminary calculations, based on Table 24:

- RCI^- = 82 (for scenario 2c)
- ΔPSL due to crack sealing = 8.18 years (based on Equation 23 using ADT of 2,000, RCI^- of 82)

Final calculations to determine the total NPV:

- Year at whicht first AC overlay was applied $= 2005$
- Year at whicht first crack sealing was applied $= 2005 + [\frac{95-82}{95-60} \times (21 + 8.18)]$= 2015.8
- Year at whicht second AC overlay was applied $= 2005 + (21 + 8.18)$= 2034.18
- Year at whicht second crack sealing was applied $= 2034.18 + [\frac{95-82}{95-60} \times 29.18]$= 2044.98
- Year at the end of the analysis=2005+50=2055
- Remaining service life after analysis period= (29.18× 2)-50 = 8.36 years
- NPV (at 2018) for the first AC overlay= 200,000*(1.04^13) = $333,014
- NPV (at 2018) for the second AC overlay= $300,000
- NPV (at 2018) for the first and second crack sealing = 12,000*2 = $24,000
- NPV (at 2018) of the salvage value = (300,000+12,000)*(8.36/29.18) = - $89,387
- Total NPV = $333,014+ $300,000+ $24,000 - $89,387 = $567,627

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