Field Performance and Cost Effectiveness of Crack Sealing in Flexible and Composite Pavements

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FIELD PERFORMANCE AND COST-EFFECTIVENESS OF CRACK SEALING IN FLEXIBLE AND COMPOSITE PAVEMENTS

A Dissertation

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Doctor of Philosophy

in

The Department of Civil and Environmental Engineering

by

Momen Ragab Mousa
B.S., Cairo University, 2012
M.S., Cairo University, 2015
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ABSTRACT

Surface cracking is one of the major surface distresses in asphalt concrete (AC) pavement, allowing water infiltration through the cracks, causing stripping in asphalt pavement layers, and weakening and deteriorating the base and/or subgrade. Its treatment, therefore, is one of the major activities in pavement preservation for many state DOTs. Among the various treatment methods currently available to preserve AC pavement with existing surface cracking are various forms of crack sealing. Crack sealing is not a common practice to Louisiana highways since the benefit of such treatment appears to be affected by the elevation of the ground water table. Studies completed in the 1960s for Louisiana showed that sealing roads in an area with a high ground water table accelerated AC stripping. The explanation was that crack sealing in such a situation prevented moisture from escaping upwards through the cracks of the AC pavements.

The objective of this dissertation was twofold. First, this study quantified the benefits of using crack sealing with respect to its ability to provide immediate benefits 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 dissertation evaluated the potential moisture damage in pavements treated with crack sealing. 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 through evaluating its cost effectiveness using common economic measures.

To facilitate implementation of the results, a user-friendly tool in the form of a spreadsheet was designed that could be used by state agencies during planning for crack sealing.
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 determine whether crack sealing is an effective maintenance treatment to be applied to an existing AC overlay based on the specific road conditions.
CHAPTER 1. INTRODUCTION

1.1. Problem Statement
Historically, crack sealing has not been favored by the Louisiana Department of Transportation and Development (LaDOTD) but this treatment has gained interest in recent years. However, studies that provide a clear quantitative justification that crack sealing is cost effective for hot and humid climates are limited in scope and few in number (Hand et al. 2000). Therefore, the use of crack sealing in Louisiana has been sporadic and based on the assumption that the benefits of crack sealing would outweigh the costs.

A number of practitioners in Louisiana also believe that the performance of crack sealing would be affected by the shallow ground water table and rainfall infiltration. Earlier studies showed that sealing roads in an area with a high ground water table may accelerate AC stripping. The explanation was that sealing in such a situation prevented moisture from escaping upwards through the surface cracks of the pavement (McKesson 1949). Yet, current crack sealing application practices are based on visual inspection without considering groundwater table level, climatic conditions, prior pavement conditions, or any other significant factors.

1.2. Research Objectives
The main objective of this research is to develop a framework that may be utilized by highway agencies to determine whether crack sealing is an effective maintenance treatment to be applied to an existing asphalt overlay based on the specific road conditions. Examples of these conditions include pre-treatment pavement conditions, traffic volume, and climatic conditions.

The proposed framework will use this data to evaluate whether crack sealing is appropriate for these specific conditions. The evaluation process would consider the following three key criteria: (1) the ability of crack sealing to address surface distresses such as surface cracks, rutting and roughness; (2) the potential subsurface moisture damage resulting from crack
sealing; and (3) the cost effectiveness of crack sealing. To achieve the objective of this study, the following questions will be answered:

1. How does crack sealing affect the short and long-term performance of asphalt and composite pavements?
2. What is the cost/benefit of crack sealing conducted in Louisiana highways?
3. What is the optimal timing of crack sealing in terms of pre-treatment pavement conditions?
4. Where can crack sealing be used to benefit pavement preservation in Louisiana highways?
5. How do ground water table and rainfall affect the performance of crack sealing?

1.3. Scope of Study

Measurements from a field experiment conducted in District 58, in Louisiana were analyzed to evaluate the effect of groundwater and other parameters on the performance of crack sealing. Furthermore, the research team analyzed the Pavement Management System (PMS) data collected in all the districts from 2003 to 2015 to quantify the short and long-term field performance of crack sealing. Current practices for crack sealing were modified through providing guidelines for the use of crack sealing to minimize moisture entrapment under sealed cracks, therefore, reducing any potential moisture damage.

1.4. Dissertation Outline

This dissertation consists of 7 chapters. Chapter 1 provides an introduction for crack sealing and identifies its problems and challenges that researchers are trying to address. This chapter also outlines the research objectives for the dissertation. The rest of the chapters are organized to achieve the objectives of the research in their order.
Chapter 2 provides a comprehensive literature review of state practices in USA for crack sealing. Afterward, the chapter provides overview of previous studies conducted to evaluate the performance and cost-effectiveness of crack sealing; and to assess the moisture damage potential under crack sealing. The chapter outlines the shortcomings in the review of previous studies. Finally, this chapter provides a technical background for the (a) pavement performance indicators, (b) measures of performance and cost-effectiveness, (c) fundamentals of flow in porous media, (d) atmospheric coupling, (e) finite element modeling, and (f) moisture damage in AC pavements.

Chapter 3 provides a full description of the research methodology of this study along with the eight tasks that were accomplished to achieve the objectives of this dissertation.

Chapter 4 provides the results of a comprehensive survey that was conducted to gather information from districts and cities in Louisiana as related to the current practices in using crack sealants. This chapter also provides a full description of the identified candidate projects and collected data that were used in the analysis.

Chapter 5 presents the analysis and results of this dissertation. First it outlines the results of evaluating the field performance of AC overlays. Then it presents the results of evaluating the short and long-term field performance of crack sealing. After that, this chapter outlines the cost-benefit analysis of applying crack sealing to AC overlays in Louisiana. In addition, it provides the optimal timing of crack sealing application. Then, the chapter discusses the experimental program and laboratory testing that was conducted to assist develop the finite element model in this dissertation. Eventually, the results of the finite element model and its application to evaluate potential moisture damage after crack sealing application is presented.
Chapter 6 presents the enhanced decision making tool that was developed to determine whether crack sealing is an effective maintenance treatment to be applied to an existing AC overlay based on the specific road conditions.

Chapter 7 summarizes the research efforts and presents the conclusions of the study.

Portions of each chapter of this dissertation previously appeared in the following articles:


CHAPTER 2. LITERATURE REVIEW

This chapter provides a comprehensive literature review of state practices in USA for crack sealing. Afterward, the chapter provides overview of previous studies conducted to evaluate the performance and cost-effectiveness of crack sealing; and to assess the moisture damage potential under crack sealing. The chapter outlines the shortcomings in the review of previous studies. Finally, this chapter provides a technical background for the (a) pavement performance indicators, (b) measures of performance and cost-effectiveness, (c) fundamentals of flow in porous media, (d) atmospheric coupling, and (e) finite element modeling.

2.1. State Practices in USA for Crack Sealing

2.1.1. Overview

Crack sealing has been widely used by state highway agencies for preventive maintenance activities. Crack sealing is a treatment technique where hot-poured bituminous-based materials are added into and/or above working cracks using unique configurations. Crack sealing minimizes water penetration into the pavement surface, reduces traffic erosion, and prevents intrusion of incompressible materials into the crack. Crack sealing is primarily used to treat thermal transverse cracks and/or transverse reflective cracks, see Figure 1, which experience large crack movements. Table 1 summarizes the different criteria that should be used to decide whether to seal cracks (Smith et al. 2001).

Figure 1. Crack Sealing Candidate: Transverse Cracking in Asphalt Pavement (Neal 2017)
Table 1. Recommended Criteria to Determine whether to Apply Crack Sealing (Smith et al. 2001)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Recommended Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width, in</td>
<td>0.2-0.75</td>
</tr>
<tr>
<td>Edge Deterioration (i.e., spalls, secondary cracks)</td>
<td>Minimal to none (≤ 25% of crack length)</td>
</tr>
<tr>
<td>Annual Horizontal Movement, in.</td>
<td>≥ 0.12</td>
</tr>
<tr>
<td>Type of Crack</td>
<td>Transverse thermal cracks, transverse reflective cracks, longitudinal reflective cracks, and longitudinal cold-joint cracks</td>
</tr>
</tbody>
</table>

2.1.2. Crack Sealant Materials

Selection of sealer material is a critical factor that influences the efficiency of crack treatment operations. Common sealant materials are AC emulsions (cold-applied) and rubberized AC (hot-applied) (Smith et al. 2001). Emulsified AC materials are governed by ASTM D 977-13, while hot-poured crack sealant materials are governed by ASTM D 6690-15. ASTM D 6690-15 classified the hot-poured sealant materials into four major groups according to material specifications as shown in Figure 2. Specifications and manuals of state Departments of Transportation (DOTs) reveal that state agencies often use multiple crack sealant types depending on their climatic conditions. Among 49 states, 13 states specify the sealant type for crack sealing application. The most common products, based on ASTM D 6690 classification are Types II and IV crack sealants (Lee et al. 2015). A national survey conducted by National Cooperative Highway Research Program (NCHRP) did not address particular sealant products by name to avoid any proprietary issues. Instead, the survey reported that 64% of the survey participants have approved list of materials to use in crack sealing in accordance with their state DOT specifications (Decker 2014).
Placement Configuration

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. Figure 3 illustrates the different configurations used in crack sealant application. There is considerable debate over which of the different configurations to be used in crack sealing in order to provide optimum material usage.
The Federal Highway Administration (FHWA) does not recommend a specific configuration; instead, it states various factors that should be considered when deciding which placement configuration to select (Smith et al. 2001). Chong recommended a configuration that involves overfilling the cracks to just cover the crack edges (Chong 1990). This configuration allows for shrinkage at low temperature and minimizes snowplow damage for routed cracks. While Al-Qadi et al. recommended using the overband configuration in sealing cracks (Al-Qadi et al. 2014), Eaton and Ashcraft were against overbanding to a great extent (Eaton and Jane 1992).
Raza reported that many states experienced serious problems with sealant ridging or bleeding through a new overlay if thick sealant is applied before overlay construction (Raza 1994). Based on NCHRP national survey, the flush fill (with or without routed crack) configuration is the most widely used configuration, where 48% of respondents use the flush fill crack seal configuration. About 43% of respondents use the overband crack seal configuration, while only 35% always use the recessed crack configuration (Decker 2014).

2.1.4. Crack Preparation
Crack preparation is a key aspect of sealing operations performed immediately before sealant application to provide 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 (Smith et al. 2001). In recent surveys, about 36 states used standard air compressor to clean the cracks, while 19 states cleaned their cracks using Hot Air Lance (HAL) (Eaton and Jane 1992). Recent NCHRP survey also indicated that the standard air compressor is still the most common method of crack cleaning followed by the HAL, while both the sand blaster and wire brush are rarely used (Decker 2014).

2.1.5. 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 obtain the required 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 all the manufacturer’s recommendations and able to follow them (Decker 2014).

The equipment used in sealant preparation and placement primarily depends on the type of material used. Emulsion materials are generally applied using distributors equipped
with gravity or pressure hoses for wand application (Peshkin et al. 2004). Rubberized AC should be heated and mixed using indirect-heat melter. This melter should be able to heat the material safely to 400°F, while the heat transfer oil should not exceed 525°F. Gear pump with a direct connecting applicator tip should provide sufficient pressure to apply the sealant material to the pavement (Decker 2014).

2.1.6. 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. 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. Both types of squeegee are 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. 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 (Smith et al. 2001).

Figure 4. All-metal Squeegee (left) vs. Rubber-faced Squeegee (right) (Decker 2014)
2.1.7. Construction Practices in Louisiana

In Louisiana, different construction practices are adopted to ensure a successful crack sealing installation. District surveys indicated that the most common sealant materials are hot-poured asphalt sealant and asphalt emulsion (Cationic Rapid Setting [CRS]). Crack sealing is usually performed in late fall, winter, and early spring when temperatures are above 50°F with dry pavement. Prior to crack sealing, cracks are usually cleaned using air compressor, while no routing is conducted due to limited funds. Crack sealing is placed flush fill or overband using pour pots for CRS and melter for rubberized asphalt. A squeegee is then used for material finishing of rubberized asphalt, while CRS are blotted using 3/16 in. lightweight expanded clay aggregate. Eventually, random inspection is conducted with no time lag for quality control of crack sealing.

2.2. Field Performance of Crack Sealing

2.2.1. Previous Studies

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 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 2 years, depending on traffic volume, environment, and pavement’s original conditions (Ponniah and Kennepohl 1996).

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-feet 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 (Rajagopal 2011).

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 (Eaton and Jane 1992). 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 (Lu and Tolliver 2012). Yet, other studies indicated that crack sealing has no significant impact on IRI (Fang et al. 2003).

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 crack sealants with high crack movement and traffic (Smith and Romine 1999).

2.2.2. Shortcomings

Based on the aforementioned studies, there is a general agreement that crack sealing is effective in controlling cracks in AC pavements, and therefore extending the PSL. Yet, this study is expected to address several knowledge gaps in the literature as follows:

- Although the main distresses that may be affected by crack sealing are cracking and roughness, most of the studies focused on overall pavement condition indices. Generally, overall pavement condition indices include several distresses that are not
influenced by crack sealing, such as bleeding, rutting, etc. Hence, this dissertation analyzed longitudinal and transverse cracking in terms of Random Cracking Index, and roughness in terms of the Roughness Index to provide a more accurate assessment of the effects of crack sealing;

- Most of the previous studies were conducted in the Northern United States and Canada with cold climates, since crack sealing was not typically used in the Southern United States with hot and wet climates. Yet, this trend has changed in recent years. Therefore, it is necessary to evaluate the field performance of crack sealing in hot and wet climates such as Louisiana;

- None of the previous studies developed a quantitative model to quantify benefits of crack sealing. Hence, this dissertation developed a simple model to predict the benefits of crack sealing given limited information related to project conditions.

2.3, Cost-Effectiveness of Crack Sealing

2.3.1. Previous Studies

As early as 1996, a cost-benefit analysis was conducted by the Ministry of Transportation, Ontario, Canada, to recognize the economic benefits of crack sealing. Two approaches namely, cost-effectiveness and Life Cycle Cost Analysis (LCCA), were used to compare between two alternative strategies. The first alternative included only major rehabilitation treatments using structural AC overlays, while the second alternative considered routing and sealing cracks in addition to the AC overlays. The findings of this study indicated that alternative two is more cost-effective than alternative one (Ponniah and Kennepohl 1996).

A cost-benefit analysis was conducted by Ohio DOT to evaluate the cost-effectiveness of crack sealing and to determine the optimal timing of sealant application. Test sections were selected over the state including 57 counties. In each test section, 1000-feet long subsection was left unsealed to serve as a control segment. Results indicated that
crack sealing could prolong the PSL by up to 3.6 years. These results were used to conduct the cost-benefit analysis using the LCCA approach, expressed in the form of Net Present Value. The LCCA approach indicated that crack sealing is cost-effective when applied to pavements with prior Pavement Condition Rating between 66 and 80 (Rajopal 2011).

A research study was conducted by Michigan DOT to evaluate the benefits and costs of the different preventive maintenance treatments, including crack sealing, used in Michigan. The cost-effectiveness approach was utilized in this study to conduct the cost-benefit analysis. The results indicated that crack sealing was the most cost-effective treatment for the flexible pavements, while microsurfacing was the most cost-effective treatment for composite pavements followed by crack sealing. 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 (Ram and Peshkin 2013).

Montana DOT conducted a cost-benefit analysis to establish the most economical and effective method of sealing pavement cracks for Montana; and to better assess the role of crack sealing within Montana’s pavement management system. To achieve this objective, four experimental test sites were constructed within larger crack sealing projects. These sites included combinations of eleven sealant materials and six placement configurations. The cost-benefit analysis was conducted in that study using the cost-effectiveness approach, and the results indicated that Crafco 522 was the most cost-effective material and the Shallow and Flush was the most cost-effective placement configuration (Cuelho and Reed 2004).

Pennsylvania DOT conducted a study to assess the benefits and costs associated with crack sealing and other preventive maintenance strategies. In this study, the Equivalent Annual Cost (EAC) approach, and the LCCA approach, expressed in the form of Benefit/Cost ratio were used to conduct the cost-benefit analysis. The results of the EAC approach indicated that crack sealing is the most cost-effective treatment when compared
with other maintenance strategies. Furthermore, the results of the LCCA indicated that lower cost treatments such as crack sealing are most efficient when applied relatively early in the pavement life, while the higher cost treatments such as NovaChip® are more efficient when applied later in the pavement life (Morian 2011).

Another study by Hicks et al. proposed a simple framework based only on the EAC approach to compare between the cost-effectiveness of several maintenance treatments, including crack sealing. Although cost must be considered, the authors recommended that it should not always be the overriding factor in deciding which treatment to use. Engineering judgment plays an important role in the overall selection process (Hicks et al. 1999).

2.3.2. Shortcomings

From the reviewed literature, there is a general agreement that crack sealing is a cost-effective maintenance strategy. Yet, this dissertation is expected to address several shortcomings in the current state of knowledge as follows:

- Most of the previous studies evaluated the cost-effectiveness of crack sealing assuming that crack sealing results in a fixed crack sealing benefit (increase in pavement service life) regardless the pre-treatment pavement conditions. This assumption is incorrect since it is well-recognized that crack sealing benefits vary depending on pre-treatment pavement conditions. Therefore, this study evaluated the cost-effectiveness of crack sealing for various pre-treatment pavement conditions.

- Previous studies used at the most two approaches to evaluate the economic benefits of crack sealing. In this study, a cost-benefit analysis was conducted using four economic measures to overcome the limitations of each approach and to provide a more comprehensive analysis of crack sealing cost-effectiveness.

- None of the previous studies developed a quantitative model to predict the economic benefits of crack sealing. Hence, this study developed a simple regression model to
predict the cost-effectiveness of crack sealing given the project conditions.

2.4, Effects of Moisture on the Performance of Crack Sealing

2.4.1. Previous Studies

Limited research studies were conducted to specifically evaluate moisture entrapment under crack-sealed AC pavements using Finite Element Analysis (FEA). Therefore, the literature presented in this section will focus on (a) moisture entrapment under surface treatments and (b) using finite element to evaluate the drainage performance of AC pavements. As early as 1949, McKesson (McKesson 1949) highlighted the detrimental effects of seal coats constructed on roadways with high groundwater table (GWT) levels. Under such conditions, the seal coat developed a vapor seal causing blistering in asphalt pavements. In 1985, Kennedy (Kennedy 1985) supported McKesson’s hypothesis, and reported that surface sealing could prevent the evaporation of water that moves upwards through the pavement. This conclusion was based on numerous cases in Texas and other states, in which stripping was observed under existing pavements after receiving a surface seal. Similar findings were reported in Colorado and Nebraska, as they noticed stripping in asphalt pavements due to water trapped underneath seal coats (Johnson and Reed 2002).

In 1986, the Texas Department of Transportation (TxDOT) sponsored a research project (Solaimanian et al. 1993) to investigate moisture damage in AC pavements treated with antistripping agents. 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 microsurfacing. The field test sections were monitored for signs of distress during the research study. Finally, core samples were extracted 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 possibly due to the moisture entrapped in that layer.
In 2013, a research study in Minnesota reported that stripping failure was detected beneath chip seals. This conclusion was based on district surveys, laboratory tests, coring, and field tests (Wood and Melissa 2013). FHWA sponsored a research study to evaluate the benefits of preventive maintenance treatments and to develop application processes for these treatments. One of the major findings of this research indicated that sealing cracks while there is moisture inside the pavement structure can accelerate stripping (Zaniewski and Mamlouk 1996).

Finite element analysis, specifically using SEEP/W software, has been widely employed in pavement engineering to evaluate drainage systems. A study was conducted in Ohio to evaluate the drainage performance of different permeable base materials. The flow of water through six pavement sections was modeled using SEEP/W. Based on the results, the study reported that this FE method is accurate in simulating the water flow through the pavement layers (Rababah and Liang 2007). Similarly, the Minnesota Department of Transportation (MnDOT) developed a comprehensive approach to design pavement that integrates the transient effects of moisture on mechanistic-empirical pavement design based on FE method; the findings of the study also showed that the results of SEEP/W were comparable to field measurements (Ariza and Birgisson 2002).

Another study in Kentucky successfully modeled various pavement drainage systems using SEEP/W and the relative drainage benefits of these systems were successfully quantified (Mahboub et al. 2003). Likewise, a recent study in Indiana successfully used SEEP/W to ensure that subsurface drainage is adequate for a concrete pavement structure (Yigong et al. 2013). SEEP/W was also successfully used to model the drainage performance of asphalt pavements in Europe (Patrick et al. 2014) and in Asia (Chulsang et al. 2016). Therefore, SEEP/W software was adopted in this dissertation to evaluate moisture entrapment in sealed and untreated pavement.
2.4.2. Shortcomings

Based on the review of literature, studies have shown that sealed asphalt pavements could have a potential for moisture damage. Yet, this study is expected to address several limitations in the previous studies as follows:

- All the previous studies related to moisture entrapment under surface treatments and crack sealing were primarily based on cores and laboratory testing to verify that moisture damage is caused due to the application of surface treatments without providing quantitative solutions for this problem. To address this issue, a parametric study was conducted using the finite element method to provide guidelines detailing the proper use of crack sealing while reducing the potential for moisture damage.

- All the previous studies that modeled pavement drainage systems neglected the unsaturated moisture-flow through the asphalt layers assuming that it is impermeable, and that water flows to the underlying layers solely through surface cracks. Yet, this assumption is not valid particularly for asphalt pavements in Louisiana due to their high hydraulic conductivities (Louay et al. 2003). To overcome this shortcoming, the unsaturated and saturated material properties of the asphalt layers were considered and included in the finite element model.

- All the previous studies that modeled pavement drainage systems considered only the water flow into the pavement structure by conducting a seepage analysis neglecting any surface evaporation occurring from the pavement surface. Since evaporation constitutes a significant component of the mass flow, a coupled transient water, vapor, and heat flow analysis was considered in this study to account for surface evaporation by integrating SEEP/W with TEMP/W in GeoStudio software.
2.5. Pavement Performance Indicators in Louisiana Pavement Management System

In Louisiana, crack sealing activities are captured via the Maintenance Management System’s work orders. Pavement performance data are reported in LaDOTD 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 (Khattak et al. 2008). Video crack surveys are available for each state highway in Louisiana and could be reviewed using VisiDataTM software. 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 (Khattak et al. 2009):

\[ RCI = \min\{100, \max(0.100 - DP_L, 0.100 - DP_M, 0.100 - DP_H)\} \]  

(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:

\[ IRI \text{ (in/mile)} = (100 - RFI) \times 5 + 50 \]  

(2)

2.6. Pavement Performance as a Function of Time

Several studies have used a polynomial approach to model pavement conditions (Khattak et al. 2009; Lu and Tolliver 2012; Morian 2011). In this dissertation, it was
assumed that both pre and post-treatment conditions could be represented by polynomial models as depicted in Equations (3) and (4); see Figure 5:

\[ f_{\text{pre}}(t) = a_1 t^2 + b_1 t + c_1 \]  \hspace{1cm} \text{(3)}

\[ f_{\text{post}}(t) = a_2 t^2 + b_2 t + c_2 \]  \hspace{1cm} \text{(4)}

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 5; 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 5. Pre and Post-treatment Performance Curves due to Treatment Application

2.7. Measures of Effectiveness

Several measures have been developed to utilize the aforementioned indicators in evaluating 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 2.
These measures were used in this study to evaluate the field performance of crack sealing and are described in the following sections.

Table 2. Common Pavement Performance Measures (Rajagopal 2011; Labi et al. 2006; Haider and Dwaikat 2011; Rajagopal and George 1991)

<table>
<thead>
<tr>
<th>Pavement Performance Measure Class</th>
<th>Pavement Performance Measure</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-term</td>
<td>Performance Jump</td>
<td>PJ</td>
</tr>
<tr>
<td>Long-term</td>
<td>Average Performance Gain</td>
<td>APG</td>
</tr>
<tr>
<td></td>
<td>Increase in Pavement Service Life (PSL), compared to the same section before treatment</td>
<td>ΔPSL</td>
</tr>
<tr>
<td></td>
<td>Increase in Pavement Service Life (PSL), compared to a nearby untreated section</td>
<td>PSL*</td>
</tr>
</tbody>
</table>

2.7.1. Performance Jump (PJ)

It is the immediate improvement in pavement conditions after applying crack sealing and could be calculated by subtracting the first collected index after crack sealing from the last index before crack sealing (Rajagopal and George 1991). The PJ could be visualized as the distance BD in Figure 5.

2.7.2. Average Performance Gain (APG)

Figure 6 illustrates the method used to compute the APG (Rajagopal 2011). 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.
2.7.3. 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 5. The following equations are used to calculate the ΔPSL:

\[
SL_{pre} = -\frac{b_1 - \sqrt{-b_1^2 - 4a_1(c_1 - TV)}}{2a_1} \\
SL_{post} = -\frac{b_2 - \sqrt{-b_2^2 - 4a_2(c_2 - TV)}}{2a_2} + t_i \\
ΔPSL = SL_{post} - SL_{pre}
\]

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.

2.7.4. 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 untreated segments as indicated in Figure 7 (Rajagopal 2011).
2.8. 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.

2.8.1. Equivalent Annual Cost (EAC)

The EAC for a specific maintenance treatment is calculated as follows (Morian 2011):

\[
\text{EAC of maintenance treatment} = \frac{\text{Unit cost \$/lane – mile}}{\Delta \text{PSL (years)}}
\]  

(8)

2.8.2. Life Cycle Cost analysis (LCCA)

LCCA is an engineering economic analysis technique to assess the overall long-term economic viability of competing project alternatives (AASHTO 1986). The most common indicator of LCCA includes Benefit Cost (B/C) ratio (Zimmerman and Walters 2004). 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 (Morian 2011). Hence, the B/C ratio is calculated as follows:

![Figure 7. Deriving the PSL*](image-url)
\[
\frac{B}{C} \text{ ratio} = \frac{\Delta \text{EUAC}}{\text{EUAC}_{\text{pvc}}} = \frac{\text{EUAC}_{\text{do nothing}} - \text{EUAC}_{\text{treatment}}}{\text{EUAC}_{\text{pvc}}}
\]  \hspace{1cm} (9)

Where \(\Delta \text{EUAC}\) = net benefit of the maintenance treatment; \(\text{EUAC}_{\text{do nothing}}\) = EUAC of the original AC overlay due to “do nothing”; \(\text{EUAC}_{\text{treatment}}\) = EUAC with application of the maintenance treatment; and \(\text{EUAC}_{\text{pvc}}\) = EUAC due to the cost of preservation. The equations used to calculate \(\text{EUAC}_{\text{do nothing}}, \text{EUAC}_{\text{treatment}},\) and \(\text{EUAC}_{\text{pvc}}\) can be found elsewhere (Mousa et al. 2018).

2.8.3. 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 (Rajagopal 2010):

\[
\text{CE} = \frac{\text{TNB}}{\text{Unit cost of the treatment} \ ($/\text{mile})} \times 100
\]  \hspace{1cm} (10)

TNB is calculated as the increased area under the performance curve due to the treatment activity. According to Figure 5, TNB can be expressed as:

\[
\text{TNB} = A_2 - A_1
\]  \hspace{1cm} (11)

\[
A_2 = \int_0^{SL_{\text{post}}} (t_{\text{post}} - TV) \, dt
\]

\[
A_1 = \int_{t_i}^{SL_{\text{pre}}} (t_{\text{pre}} - TV) \, dt
\]

\[
A_2 = \frac{a_2}{3} (SL_{\text{post}} - t_i)^3 + \frac{b_2}{2} (SL_{\text{post}} - t_i)^2 + (c_2 - TV)(SL_{\text{post}} - t_i)
\]  \hspace{1cm} (12)

\[
A_1 = \frac{a_1}{3} (SL_{\text{pre}}^3 - t_i^3) + \frac{b_1}{2} (SL_{\text{pre}}^2 - t_i^2) + (C_1 - TV)(SL_{\text{pre}} - t_i)
\]  \hspace{1cm} (13)

Where, \(A_2\) = Area enclosed between post-treatment performance curve and threshold value; and \(A_1\) = Area enclosed between pre-treatment performance curve and threshold value.

2.9. Fundamentals of Flow in Porous Media

2.9.1. Introduction

The flow of soil water through soil takes place through the soil pore space. Soil water movement through these pores is brought about by an energy gradient such as gravity,
capillary forces, osmotic forces, and temperature or pressure differences (Ridgeway 1982). To accurately understand the flow in porous media, it is useful to understand the following terms:

- **Saturation**: soil water content when soil pores are filled with water. The dominant driving force for water flow in these conditions is gravity.

- **Field capacity (or specific retention)**: soil water content after all gravitational drainage has stopped. It is defined as “the maximum water content a soil can hold or store under a condition of complete wetting followed by drainage” (Marinho and Stuermer 1998).

- **Air-dry (or wilting point)**: soil water content when all moisture is removed from the soil surface, while soil pores are partially saturated with hygroscopic water.

- **Over-dry**: soil water content after oven drying (105 °C), which is considered to be zero.

### 2.9.2. Relation between Groundwater and Road

Figure 8 depicts a schematic view of the regions of subsurface water in a pavement structure. At some depth lies the groundwater table; beneath this, the soil is fully saturated, and forms the ‘groundwater zone’, or ‘zone of saturation’. The groundwater table could be defined as the line of zero pore water pressure (relative to the atmosphere). Above the groundwater table, the vadose zone exists which is divided into the capillary zone, intermediate vadose zone, and surface water zone. Capillary zone exists directly above the groundwater table, where groundwater is pulled upwards against gravity by surface tension. Within the intermediate vadose zone, water is held by capillary forces, and the moisture content is normally stable at or near the field capacity. While the surface water zone represents the closest layer to the surface.
2.9.3. **Saturated and Unsaturated Water Flow through Pavements**

The saturated zone is located below the groundwater table, where the pore spaces are fully filled with water. Therefore, the volumetric water content in this zone is constant and is equal to the saturation level resulting in positive pore water pressures increasing with the depth below the groundwater level. Consequently, the soil hydraulic conductivity within the saturated zone is constant. Therefore, to fully describe the saturated behavior of soils, it is essential to define the depth of the groundwater table and the saturated hydraulic conductivity of the soil.

The unsaturated zone is located above the groundwater table, where the pore spaces are partially filled with water, while the remaining pores are filled with air. Accordingly, the volumetric water content in this zone is less than the soil porosity. Since water in this zone is held in the soil pores under surface-tension forces, negative pore pressures (soil suction) are developed. Generally, this soil suction and the hydraulic conductivity are dependent on the volumetric water content (or saturation). Therefore, in order to fully describe the unsaturated behavior of soils, it is essential to define the suction in the soil at all likely
saturation levels “Soil Water Characteristics Curve” (SWCC), along with the hydraulic conductivity as a function of the resulting soil suction “Hydraulic Conductivity Curve” (Ariza and Birgisson 2002).

2.9.4. Soil-Water Characteristic Curve (SWCC)

The SWCC is “S” shaped curve describing the correlation between the water volume in soil and the energy state of the water present in the soil. It is usually presented in terms of matric suction against the degree of saturation or volumetric content. The shape of SWCC primarily depends on the shape of soil particle, soil particle packing, and the pore size distribution, which is determined by the soil gradation (Gupta and Wang 2001). Figure 9 illustrates a typical SWCC curve, displaying the relationship between the pore water pressure (soil suction) and saturation. It may be noted from Figure 8 that the rewetting (adsorption) and drainage (desorption) paths in an SWCC are not the same due to hysteresis (Freeze and Cherry 1979).

Since it is usually difficult or time consuming to obtain a SWCC in a laboratory, it may be beneficial to develop an estimation of the SWCC. Therefore, there are several parametric models that have been developed to describe the matric potential’s dependency on moisture content. Common models for SWCC include Brooks and Corey, Van Genuchten, Fredlund and Xing, and Vauclin models. Similarly, several models were developed to describe the Hydraulic Conductivity Curve such as Brooks and Corey, Van Genuchten, and Gardner (SEEP/W 2012).
2.10. Atmospheric Coupling

The key to numerical modeling of the vadose zone is the ability to accurately predict the surface boundary condition. The most significant variable to quantify is the magnitude of surface infiltration and actual evaporation, or in modeling terms, the surface unit flux boundary. This could be achieved by coupling the moisture and heat stress states at the ground surface with climate conditions present above the ground surface. Therefore, a coupled mass, heat and vapor flow analysis is discussed in the subsequent sections (VADOSE/W 2014).

2.10.1. Overview on Water Flow (Seepage)

Seepage refers to the slow movement of water through porous media. Seepage analyses are usually classified into steady-state or unsteady-state (transient) flow analyses. For steady state analyses, all fluid properties including the hydraulic head and hydraulic conductivity, are independent of time at any point in the soil mass. For transient flow analyses, the hydraulic head and possibly the hydraulic conductivity change with respect to time. These changes are usually in response to a variation in the boundary conditions with respect to time.
The governing equations for steady-state and transient flow are Laplace’s and Richards’s equations, respectively. These equations are derived based on Darcy’s law and the concept of mass balance (Liu 2005).

2.10.2. Seepage Differential Equations

Bernoulli equation describes the total hydraulic head of the system between two points A and B based on an experimental setup:

\[
\frac{u_A}{\rho g} + \frac{v_A^2}{2g} + z_A = \frac{u_B}{\rho g} + \frac{v_B^2}{2g} + z_B + \Delta h
\]  

(14)

Where \(u\) and \(v\) are the water pressure and velocity respectively; \(\rho\) is the water density; \(g\) is the gravitational acceleration; \(\rho g\) is equal to the unit weight of water (\(\gamma_w\)); \(z\) is the elevation above the datum line; and \(\Delta h\) is the head loss between points A and B which generates the flow. Water flow in porous media exhibits very small velocities, therefore velocity heads are neglected allowing the head loss to be expressed as follows (Fredlund and Rahardjo 1993):

\[
\Delta h = \left(\frac{u_A}{\rho g} + z_A\right) - \left(\frac{u_B}{\rho g} + z_B\right)
\]

(15)

The flow of water within a fully saturated soil behaves in accordance to Darcy’s law which has the following form (Darcy 1856):

\[
v_x = -k_x \frac{\partial h}{\partial x}
\]

(16)

Where \(v_x\) is the flow velocity of water in the x-direction; \(k_x\) is the hydraulic conductivity for water flow in the x-direction; \(\partial h\) is the infinitesimal change in head over an infinitesimal distance \(\partial x\); and \(\frac{\partial h}{\partial x}\) is the hydraulic head gradient in the x-direction. The negative sign in Darcy’s law indicates that water flow takes place in the direction of a decreasing hydraulic head. Darcy’s law can also be written for the y- and z-directions. Darcy’s law takes the following form for water flow through unsaturated soil (Smith 2003):

\[
v_x = -k_x(\psi) \frac{\partial h}{\partial x}
\]

(17)
Where, $K_x(\psi)$ is the hydraulic conductivity being function of soil matric suction. In the SWCC, the slope of the curve could be denoted by $m_w$ to represent the rate of change in the amount of water retained by the soil in response to a change in pore-water pressure as follows (Liu 2005):

$$m_w = -\frac{\Delta \theta_w}{\Delta(u_a-u_w)}$$  \hspace{0.5cm} (18)

Where $m_w$ is the slope of the SWCC; $\theta_w$ is the water content; $u_a$ is the air pressure; and $u_w$ is the pore water pressure. For constant air pressure, Equation 18 becomes:

$$m_w = \frac{\partial \theta_w}{\partial u_w}$$  \hspace{0.5cm} (19)

Based on the chain rule in differentiation, the change in moisture content with respect to time ($t$) could be written as follows:

$$\frac{\partial \theta_w}{\partial t} = \frac{\partial \theta_w}{\partial u_w} \frac{\partial u_w}{\partial t} = |m_w| \frac{\partial u_w}{\partial t}$$  \hspace{0.5cm} (20)

Using the definition of hydraulic head, the following could be obtained:

$$\frac{\partial h}{\partial t} = \frac{1}{\gamma_w} \frac{\partial u_w}{\partial t}$$  \hspace{0.5cm} (21)

Substituting Equation 21 into Equation 20, the following could be derived:

$$\frac{\partial \theta_w}{\partial t} = |m_w| \gamma_w \frac{\partial h}{\partial t}$$  \hspace{0.5cm} (22)

Let us consider the three-dimensional water flow through the cubical soil element shown in Figure 10. In this figure, $dx$, $dy$, and $dz$ represent the infinitesimal dimensions of the soil element. The flow velocities $v_x$, $v_y$, and $v_z$ are assumed positive when the flow of water is in the positive directions of $x$, $y$, and $z$, respectively. The flow quantity is expressed in terms of a flux ($q$), which is equal to the flow velocity ($v$) multiplied by the cross-sectional area ($A$).
Based on the concept of mass balance, the continuity for the three-dimensional flow in Figure 10 could be described as follows:

\[
\left( v_x + \frac{\partial v_x}{\partial x} \right) dy \, dz \, dt + \left( v_y + \frac{\partial v_y}{\partial y} \right) dz \, dx \, dt + \left( v_z + \frac{\partial v_z}{\partial z} \right) dx \, dy \, dt - v_x dy \, dz \, dt - v_y dz \, dx \, dt - v_z dx \, dy \, dt = \frac{\partial \theta_w}{\partial t} \, dx \, dy \, dz \, dt
\]  

(23)

This equation could be simplified to give the following:

\[
\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = \frac{\partial \theta_w}{\partial t}
\]  

(24)

Substituting Equation 22 into Equation 24, one can get:

\[
\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = |m_w| \gamma_w \frac{\partial h}{\partial t}
\]  

(25)

Applying Darcy’s law to Equation 25, the following could be derived (Fredlund and Rahardjo 1993):

\[
\frac{\partial}{\partial x} \left[ k_x(\psi) \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial y} \left[ k_y(\psi) \frac{\partial h}{\partial y} \right] + \frac{\partial}{\partial z} \left[ k_z(\psi) \frac{\partial h}{\partial z} \right] = |m_w| \gamma_w \frac{\partial h}{\partial t}
\]  

(26)

The term Q could be added to Equation 26 to allow for an applied boundary flux as follows (Ng and Shi 1998):

\[
\frac{\partial}{\partial x} \left[ k_x(\psi) \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial y} \left[ k_y(\psi) \frac{\partial h}{\partial y} \right] + \frac{\partial}{\partial z} \left[ k_z(\psi) \frac{\partial h}{\partial z} \right] + Q = |m_w| \gamma_w \frac{\partial h}{\partial t}
\]  

(27)
Equation 27 could be written in terms of changes in matric potential ($\partial\psi$) instead of changes in total hydraulic head ($\partial\text{h}$) resulting in Richard’s equation as follows (Freeze and Cherry 1979):

$$\frac{\partial}{\partial x}\left[k_x(\psi)\frac{\partial\psi}{\partial x}\right] + \frac{\partial}{\partial y}\left[k_y(\psi)\frac{\partial\psi}{\partial y}\right] + \frac{\partial}{\partial z}\left[k_z(\psi)\left(\frac{\partial\psi}{\partial z} + 1\right)\right] + Q = |m_w|\gamma_w\frac{\partial\text{h}}{\partial t}$$

(28)

Equation 28 (or Equation 27) can be used to model transient analyses under saturated and unsaturated flow conditions. Under steady state analysis, Equation 27 is reduced to the following:

$$\frac{\partial}{\partial x}\left[k_x\frac{\partial\text{h}}{\partial x}\right] + \frac{\partial}{\partial y}\left[k_y\frac{\partial\text{h}}{\partial y}\right] + \frac{\partial}{\partial z}\left[k_z\frac{\partial\text{h}}{\partial z}\right] + Q = 0$$

(29)

Assuming an isotropic condition in which $k = k_x = k_y = k_z$, Laplace’s equation could be obtained as follows:

$$\frac{\partial^2\text{h}}{\partial x^2} + \frac{\partial^2\text{h}}{\partial y^2} + \frac{\partial^2\text{h}}{\partial z^2} + Q = 0$$

(30)

2.10.3. Vapor Flow (Evaporation)

Soil evaporation is an important component of evapotranspiration, which is the main method of soil water depletion in the field (VADOSE/W 2014). Traditionally, evaporative flux modeling has been limited to methods that predict the unit flux evaporation rate based on a potential evaporation (PE) value. The Penman method is the widely-used approach to predict PE, which assumes the ground surface is always saturated (Penman 1948).

It is now well known that the rate of actual evaporation (AE) is only equal to the PE rate when the soil is saturated; and that the AE rate starts to decrease relative to PE as the soil desaturates at its surface (VADOSE/W 2014). Figure 11 presents how the vapor pressure in the soil directly controls the ability of the soil to release water to the atmosphere. Wilson developed the well-known Penman-Wilson method to calculate the AE at the soil surface as follows (Wilson 1990):

$$AE = \frac{\Gamma Q + vE_a}{\nu A + \Gamma}$$

(31)
Where $\Gamma$ is the slope of the curve for saturation vapor pressure versus temperature at the mean air temperature (kPa/°C), $Q$ is the total net radiation at the soil surface (mm/day), $\nu$ is psychrometric constant, $E_a = f(u) \ P_a (B-A)$, $f(u) = 0.35(1 + 0.15 \ W_a)$, $W_a$ is the wind speed (km/h), $P_a$ is the water-vapor pressure of the air above the soil surface (kPa), $B$ is the inverse of the atmospheric relative humidity, and $A$ is the inverse of the relative humidity at the soil surface.

Figure 11. Vapor Pressure Gradient Influence on AE (VADOSE/W 2014)

2.10.4. Heat Flow

Temperatures within the soil profile are required for the solution of the moisture and heat flow equations. The surface temperature may be estimated with the following relationship (Wilson 1990):

$$T_s = T_a + \frac{1}{\nu f(u)} (Q - AE)$$  \hspace{1cm} (32)

Where $T_s$ is the temperature of the soil surface (°C) and $T_a$ is the temperature of the air above the soil surface (°C), $\nu$ is psychrometric constant, $f(u) = 0.35(1 + 0.15 \ W_a)$, $W_a$ is the wind speed (km/h), $Q$ is the total net radiation at the soil surface (mm/day), and $AE$ is the actual vertical evaporative flux (mm/day).
2.10.5. Partial Differential Mass, Vapor, and Heat Flow Equations

The mass transfer equation (with vapor flow) can be derived directly from the Richards equation for transient flow in unsaturated soils (Equation 28) with adaptations for vapor flow added by Wilson (Wilson 1990) with a modification proposed by Milly (Milly 1982) as follows:

\[ \frac{1}{\rho} \frac{\partial}{\partial x} \left[ D_v \frac{\partial P_v}{\partial x} \right] + \frac{1}{\rho} \frac{\partial}{\partial y} \left[ D_v \frac{\partial P_v}{\partial y} \right] + \frac{\partial}{\partial x} \left[ k_x \frac{\partial (P + y)}{\partial x} \right] + \frac{\partial}{\partial y} \left[ k_y \frac{\partial (P + y)}{\partial y} \right] + Q = m_v \frac{\partial P}{\partial t} \] (33)

Where \( P \) is the pore water pressure (kPa), \( P_v \) is the vapor pressure of the soil moisture (kPa), \( k_x \) and \( k_y \) (m/s) are the hydraulic conductivities in the x- and y-directions, respectively, \( Q \) is the applied boundary flux (m/s), \( D_v \) is the diffusion coefficient of the water vapor through the soil [kg m/(kN s)], \( y \) is the elevation head (m), \( \rho \) is the density of water (kg/m\(^3\)), \( g \) is the acceleration due to gravity (m/s\(^2\)), and \( t \) is the time (s), and \( m_v \) is the slope of the volumetric water content function. The heat transfer equation is a standard Fourier equation for conductive heat transfer with modifications for the inclusion of vapor transfer and convective heat transfer due to flowing water as follows (VADOSE/W 2014):

\[ L_v \frac{\partial}{\partial x} \left[ D_v \frac{\partial P_v}{\partial x} \right] + L_v \frac{\partial}{\partial y} \left[ D_v \frac{\partial P_v}{\partial y} \right] + \frac{\partial}{\partial x} \left[ k_{tx} \frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial y} \left[ k_{ty} \frac{\partial T}{\partial y} \right] + \rho c_v x \frac{\partial T}{\partial x} + \rho c_v y \frac{\partial T}{\partial y} + Q_t = \lambda_t \frac{\partial T}{\partial x} \] (34)

Where \( \rho c \) is the volumetric specific heat value [J/(m\(^3\).°C)], \( k_{tx} \) is the thermal conductivity in the x-direction [W/(m.°C)], \( k_{ty} \) is the thermal conductivity in the y-direction and assumed equal to \( k_{tx} \) [W/(m.°C)], \( V_x \) is the Darcy water velocity in the x-direction (m/s), \( V_y \) is the Darcy water velocity in the y-direction (m/s), \( Q_t \) is the applied thermal boundary flux (J/s), \( L_v \) is the latent heat of vaporization (J/kg), and \( \lambda_t \) is the volumetric heat capacity of the soil.

Examination of the governing heat and mass transfer equations reveals that there are three unknown parameters, namely pressure (\( P \)), temperature (\( T \)), and vapor pressure (\( P_v \)). In order to solve these equations, a third relationship between these parameters is necessary. Their
relationship can be described by using the widely accepted thermodynamic relationship given by (Edlefsen and Anderson 1943):

\[ P_v = P_{vs} h_r = P_{vs} \left( e^{-\frac{P_w}{R \cdot T}} \right) \]  

(35)

Where \( P_{vs} \) is the saturation vapor pressure (kPa) of the soil water at soil temperature \( T \), \( h_r \) is atmospheric relative humidity, \( W \) is the molecular weight of water (0.018 kg/mol), \( R \) is the universal gas constant [8.314 J/(mol·\(^\circ\)K)], and \( T \) is temperature (\(^\circ\)K).

2.11. Finite Element Modeling to Simulate Atmospheric Coupling

2.11.1. Overview

The differential equations discussed in the previous sections can be solved analytically, or numerically. Unfortunately, the analytical solution for such problems is extremely tedious because of the complexity of the boundary conditions involved. For practical purposes, however – such as in engineering – a numeric approximation to the solution is often sufficient. The finite element method is one of the most promising numerical approaches used for solving the differential equations encountered in engineering problems. Although the finite element method was originally devised to analyze structural problems, this method recently became an effective tool to evaluate a wide range of problems in the field of geotechnical and pavement engineering. This development has been primarily encouraged by the continued progress of high-speed digital computers, which provide a means of performing rapidly the frequent calculations involved in the finite element method.

2.11.2. Basic Concepts of the Finite Element Method

The finite element method consists of defining a solution that satisfies the partial differential equation on average over a finite element. Every element is connected to a neighboring element, and the field under study is analyzed by propagating the current values from one element to another through connection points (Liu 2005). The formulation of the finite
element method consists of five basic steps (Logan 2011). These steps are discussed briefly for a “seepage through porous media” problem, as an example as follows:

(a) **Element Discretization:** this step includes dividing the entire problem into an equivalent system of finite elements with associated nodes and choosing the most appropriate element type to model most closely the actual physical behavior. The total number of elements used and their variation in size and type within a given body are primarily matters of engineering judgment. The elements must be made small enough to give usable results and yet large enough to reduce computational effort. Elements that are commonly used in practice are categorized into line elements (truss and beam elements), two-dimensional elements (triangular and quadrilateral elements), and three-dimensional elements (tetrahedral and hexahedral elements).

(b) **Total hydraulic Head Approximation:** in this step a total hydraulic head function is chosen within each element to define the total hydraulic head of the element through interpolating the nodal heads of this element. Linear, quadratic, and cubic polynomials are frequently used total hydraulic head functions because they are simple to work within finite element formulation. The accuracy of the finite element method primarily depends on the nature of the total hydraulic head approximation, which should satisfy the compatibility conditions. The total hydraulic head function within each element is expressed as follows:

\[
\{H\} = [N]\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} 
\]

Where, \{H\} is the total hydraulic head vector for each element, \([N]\) is the matrix of shape functions, and \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} is the matrix of nodal total hydraulic heads.

(c) **Element Formulation:** this step involves the derivation of the element characteristic matrices,\([K]\), and developing the element equations which govern the physical behavior of each element. The different approaches used in this step include the direct
equilibrium method, work or energy methods, or weighted residuals methods. Among these approaches, the weighted residuals methods allow the finite element method to be applied directly to any differential equation. Using any of these methods will produce the equations to describe the behavior of an element. These equations are conventionally written in the compact matrix form as follows:

\[
[K][H] = \{Q\}
\]  

(37)

Where, \(\{Q\}\) is the element applied flux vector, \([K]\) is the element characteristic matrix, and \(\{H\}\) is the vector of unknown nodal heads. In order to evaluate the element characteristic matrix \([K]\), and the element applied flux vector \(\{Q\}\), integrations over element volumes and surfaces must be performed. This process cannot be done explicitly and therefore, a numerical integration scheme is employed by replacing the integral of a function by a weighted sum of the values of the function at a number of integration points. The most commonly used integration scheme is Gaussian integration and the integration points are often referred to as Gauss points (Potts and Zdravkovic 1999).

**d) Global Equations and Boundary Conditions:** this step involves assembling the individual element equations generated in the previous step into the global equations. The global characteristic matrix, \([K]_{\text{Global}}\) is obtained using the direct stiffness method as follows (Potts & Zdravkovic 1999):

\[
[K]_{\text{Global}} = \sum_{i=1}^{N} K
\]  

(38)

The global applied flux matrix \(\{Q\}_{\text{Global}}\) is the sum of all the element applied flux as follows:

\[
\{Q\}_{\text{Global}} = \sum_{i=1}^{N} Q
\]  

(39)

The final global equation written in matrix form is as follows:

\[
\{Q\}_{\text{Global}} = [K]_{\text{Global}} \{H\}
\]  

(40)
The final stage in setting up the global system of equations is the application of the boundary conditions. These are the total hydraulic heads or flow flux, which fully define the boundary value problem being analyzed.

(e) Solution of Global Equation: in this step the global equation is solved for the global nodal total hydraulic heads, \( \{H\} \) using an elimination method (such as Gauss’s method), or an iterative method (such as the Gauss–Seidel method).

2.11.3. Finite Element Equations for Seepage Analysis

Transient water seepage through a soil system can be analyzed through solving the general governing flow equation, Equation 27. This analysis can be performed using the finite element method.

(a) Element Formulation: the finite element formulation for transient seepage in two-dimensions can be derived using the Galerkin method of weighed residual. The Galerkin solution to the two-dimensional form of Equation 27, is given by the following integrals over the area and the boundary surface of a triangular element as follows (Lam et al. 1988):

\[
\mathcal{T} \int_{A} ([B]^{T} \ [C] \ [B]) \ dA \ \{H\} + \mathcal{T} \int_{A} (\lambda \ (N)^{T} \ (N)) \ dA \ \{H\}, \ t = q \mathcal{T} \int_{L} ((N)^{T}) \ dL
\]

(41)

Where, \( \{H\} \) is the matrix of hydraulic heads at the nodal points, that is, \( \begin{bmatrix} H_1 \\ H_2 \\ H_3 \end{bmatrix} \); \( t \) is the time; \( \mathcal{T} \) is the element thickness; \( A \) is a designation for summation over the area of an element; \([B]\) is the matrix of the derivatives of the area coordinates; \([C]\) is the element hydraulic conductivity matrix; \( \lambda \) is the storage term for a transient seepage \( (m_w \gamma_w) \); \( (N) \) is the vector of interpolating function; \( q \) is the unit flux across the element edge; and \( L \) is designation for summation over the element edge. Either the hydraulic head or the flow rate must be specified at the boundary nodal points.

(b) Temporal Integration: the numerical integration of Equation 41 results in a simpler expression of the equation:
\[ [K][H] + [M][H], \ t = \{Q\} \]  \hspace{1cm} (42)

Where, \([K]\) is the element characteristic matrix; \([M]\) is the element mass matrix; \(\{Q\}\) is the element applied flux vector; and \(\{H\}, \ t\) is matrix of the time derivatives of the hydraulic heads at the nodal points. The time derivative in Equation 42 can be approximated using a finite difference scheme. The relationship between the nodal heads of an element at two successive time steps can be expressed using the backward difference approximation scheme as follows (Segerlind 1984):

\[(\Delta t [K] + [M]) \{H_1\} = \Delta t \{Q_1\} + [M] \{H_0\}\]  \hspace{1cm} (43)

As indicated by Equation 43, in order to solve for the new head at the end of the time increment, it is necessary to know the head at the start of the increment. Stated in general terms, the initial conditions must be known in order to perform a transient analysis.

\(\text{(c) Numerical Integration:}\) the Gaussian numerical integration is used to evaluate the element characteristic matrix \([K]\) and the mass matrix \([M]\). The integrals are evaluated by sampling the element properties at specifically defined points (Gauss points) and then adding them together for the entire element. The following integrals:

\([K] = \int_A ([B]^T \ [C] \ [B]) \ dA\)  \hspace{1cm} (44)

\([M] = \int_A (\lambda \langle N \rangle^T \langle N \rangle) \ dA\)  \hspace{1cm} (45)

can be replaced by (SEEP/W 2012):

\([K] = \int \sum_{j=1}^n [B_j]^T [C_j] [B_j] \ \det|J_j| \ W_{1j} W_{2j}\)  \hspace{1cm} (46)

\([M] = \int \sum_{j=1}^n \lambda_j \langle N \rangle^T \langle N \rangle \ \det|J_j| \ W_{1j} W_{2j}\)  \hspace{1cm} (47)

Where, \(j\) is an integration point, \(n\) is the number of integration points, \([C_j]\) is the element hydraulic conductivity matrix at the integration point, \([B_j]\) is the matrix of the derivatives of the area coordinates at the integration point, \(\det|J_j|\) is the determinant of the Jacobian matrix, \(W_{1j}, W_{2j}\) are weighting factors, and \(\lambda_j\) is the storage term at the integration point. The number
of integration points (integration order) required in an element depends primarily on the element type and the number of nodes.

**(d) Solution of Global Equation:** Equation 42 can be written for each element and assembled to form a set of global flow equations for the whole system while satisfying nodal compatibility (Desai and Apel 1972). The global flow equations are solved for the hydraulic heads at the nodal points \( \{H\} \). However, Equation 42 is non-linear because the coefficients of permeability are related to the matric suction which is a function of the hydraulic head at the nodes. Consequently, Equation 42 must be solved using an iterative scheme involving series of successive approximations. In the first approximation, the coefficients of permeability are predicted to compute the first set of hydraulic heads at the nodes which are used to calculate the average matric suction within an element. In the following approximations, the coefficients of permeability are adjusted based on the average matric suction in the element and are used to calculate new set of nodal hydraulic heads. This procedure is repeated until the hydraulic head and the permeability differences within each element at two successive iterations are less than a specified tolerance. This iterative process causes the global flow equations to be linearized and solved simultaneously using a Gaussian elimination technique (Fredlund and Rahardjo 1993).

**(e)Atmospheric Coupling:** transient water, vapor, and heat flow through a soil system can be analyzed by solving the general governing flow equations (Equations 33, 34, and 35). The analysis can be performed using the finite element method as described in the previous sections for transient water flow. A similar approach can be used for the transient water, vapor, and heat flow with the exception of some differences in the finite element formulation. After applying the Galerkin method of weighed residual to the governing differential equations, the finite element for two-dimensional seepage equation with vapor coupling can be derived as (VADOSE/W 2014):
While the corresponding two-dimensional heat transfer finite element equation can be written as (VADOSE/W 2014):

\[
\nabla \int_A ([B]^T [C] [B]) \, dA \{P\} + \nabla \int_A ([B]^T [D_2] [B]) \, dA \{T\} + \\
\nabla \int_A ([B]^T [K] [B]) \, dA \{y\} + \nabla \int_A (\lambda \langle N \rangle^T \langle N \rangle) \, dA \{P\}, t = q_T \int_L (\langle N \rangle^T) \, dL,
\]

(48)

Where, \([C]\) is the element stiffness matrix, \([P]\) is the vector of nodal pressures, \([D_1]\) and \([D_2]\) are function of the diffusion coefficient of the water vapor through the soil, \([T]\) is the vector of nodal temperatures, \([K]\) is the element hydraulic conductivity matrix, \([y]\) is the vector of elevation heads, \([P]\), \(t\) is the change in pressure with time, \([C_t]\) is the element thermal stiffness matrix, and \([T]\), \(t\) is the change in temperature with time, \(q_h\) is the unit heat flux across the element side, and all other parameters are as previously described.

2.12. Moisture Damage in AC Pavements

Recently, the problems of moisture damage on AC pavements has drawn considerable attention towards a phenomenon known as “stripping.” This term refers to AC mixtures that experience separation of asphalt films from the aggregate when subjected to water resulting in accelerated pavement deterioration. One of the major problems of stripping is that it may not manifest at the surface for several years since it typically begins at the bottom of the AC layer and propagates upwards. Once it reaches the pavement surface, it can visually appear as several forms of distress ranging from rutting, fatigue cracking, and potholes in the wheel-path to raveling across an entire pavement surface (Kandhal et al. 1989).

Stripping in AC pavements manifests itself in multiple forms with various mechanisms, such as (a) reduction of adhesive strength between the asphalt and aggregate; (b) deterioration of asphalt due to cohesive failure within the asphalt binder itself; (c) cohesive failure within
the aggregate; (d) emulsification of the asphalt; and (e) freezing of entrapped water. Among these mechanisms, the adhesive failure between the asphalt and aggregate in the presence of water and the moisture-induced cohesive failure within the asphalt binder have been categorized as the two key driving mechanisms of stripping in AC pavements since the 1920s (Solamanian et al. 2003).
CHAPTER 3. METHODOLOGY

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

3.1. Review of LADOTD State-of-the-Practice

The research team conducted a comprehensive survey to gather information from districts in Louisiana as related to the current practices in using crack sealants and their effectiveness as a preventive maintenance activity. The research team also contacted practitioners in the districts to gauge 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 are selected. This task was considered as a first step in collecting relevant performance and cost data; it was sent to the nine districts in Louisiana.

3.2. Project Identification and Data Collection

Pavement segments that were constructed with crack sealing were identified from LaDOTD database. Since crack sealing is usually applied on AC overlays in Louisiana, AC overlay projects were also identified from LADOTD database to evaluate their field performance. This is crucial when evaluating the cost effectiveness of crack sealing. Video crack surveys were used in this study to locate the exact date and location of crack sealing and AC overlay projects. Once these locations were identified, pavement performance data, Average Daily Traffic (ADT), type of original pavement, thickness of original pavement, and treatment costs were collected for these locations. This collected data was used to evaluate the field performance and cost effectiveness of crack sealing and AC overlay.

3.3. 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 $\Delta PSL$ 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 ($PSeleccione\_PSL^*)$. 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 in the state.

### 3.4. 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 crucial when evaluating the cost effectiveness of crack sealing because most of crack sealing applications in Louisiana are conducted over AC overlays. The research team evaluated the PSL of the selected AC overlay projects, in terms of Pavement Condition Index (PCI), Random Cracking Index (RCI), Rutting Index (RTI), and Roughness Index (RFI).

### 3.5. Cost Benefits Analysis

A comprehensive cost benefits analysis was conducted for the use of crack sealing when applied to AC overlays to evaluate the cost-effectiveness of this maintenance treatment and determine its optimal timing of application. 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 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.
3.6. Experimental Program and Laboratory Testing

A field experiment was developed in this research specifically to evaluate the effect of crack sealing on moisture damage in AC pavements. 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 inch 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 several transverse and longitudinal cracks as shown in Figure 12 (a).

- **Drainage survey**: two trapezoidal side ditches exist on both sides of the road with no subsurface drainage pipes. Figure 12 (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 12 (c).

- **Core extraction**: six cores were extracted for subsequent laboratory testing. The layer thicknesses were measured in accordance with ASTM D 3549. Figure 12 (d) shows one of the extracted cores before laboratory testing.

- **Soil sampling**: samples from the base course and subgrade 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.

3.6.1. Lottman Test

In this study, Lottman test was conducted in accordance with AASHTO T-283 to determine the soaking time after which stripping occurs to 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 with a Performance Grade (PG) of 67-22. All the samples were prepared using the same aggregate types, gradations, and binder content. All the samples had Nominal Maximum Aggregate Size (NMAS) of 0.5 inch (12.5mm), and were compacted till reaching a final height of 95 mm. The samples were then categorized 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 °F (Figure 13 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, see Figure 13 b, was then conducted on each sample of each group to determine the Tensile Strength Ratio (TSR).

![Figure 13. (a) Water Soaking for the 12 Samples and (b) Split Tensile Test](image)

### 3.6.2. Asphalt Saturated Hydraulic Conductivity

The falling head permeability test apparatus shown in Figure 14 was used to determine the saturated hydraulic conductivity ($K_{sat}$) 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.
3.7. 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 cracks, therefore, reducing stripping on low volume roadways. To achieve this objective, calibrated Finite Element Model (FEM) was used to model the aforementioned field experiment. Sensitivity analysis was then conducted to compare between crack-sealed and unsealed sections under different Ground Water Table levels, air relative-humidity, air-temperatures, rain-intensities, and asphalt hydraulic conductivities.

3.7.1. Calibration of the Finite Element Model

(a) Finite Element Analysis. To represent 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 till day 80 (corresponding to the crack sealing date). In the second transient analysis (B), a sealed cross-section was modeled starting from day 80 till day 308 (corresponding to the final site visit date). To differentiate between the cracked and sealed sections in the FEM,
different crack geometry and boundary conditions were assigned, as described in 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.

(b) Material Properties. Thermal conductivity and volumetric heat capacity are required to model 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 finite element 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 (Carsel and Parrish 1988). Since it is not cost-effective to directly measure suction values (Gustavo 2011), it is a common technique in previous studies (Ariza and Birgisson 2002; Rabab'ah and Liang 2007) to assume these values based on the material type and then calibrate the results. 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 (Pease et al. 2010), sandy loam, and loam materials (Carsel and Parrish 1988), respectively. Similarly, typical thermal conductivities and heat capacities were assigned to the asphalt, base, and subgrade to account for the thermal properties of asphalt (Hassan and White 1996), sandy loam, and loam (Alnefaie and Abu-Hamdeh 2013; Abu-Hamdeh and Reeder 2000) materials, respectively.
Table 3. Material Properties as Defined in the FEM

<table>
<thead>
<tr>
<th>Property</th>
<th>Asphalt</th>
<th>Sandy loam base</th>
<th>Loam subgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity ($J/d/m/^\circ C$)</td>
<td>125,150</td>
<td>57,813</td>
<td>44,870</td>
</tr>
<tr>
<td>Volumetric heat capacity ($J/m^3/^\circ C$)</td>
<td>1,881,580</td>
<td>1,500,000</td>
<td>1,500,000</td>
</tr>
<tr>
<td>Van Genuchten fitting parameters</td>
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<td></td>
<td></td>
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<tr>
<td>Residual moisture content</td>
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<td>0.078</td>
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<tr>
<td>Saturated moisture content</td>
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<td>0.41</td>
<td>0.43</td>
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<tr>
<td>n</td>
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<td>1.89</td>
<td>1.56</td>
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<td>a (Kpa)</td>
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<td>1.308</td>
<td>2.725</td>
</tr>
<tr>
<td>$K_{sat}$ (m/sec)</td>
<td>3.45x10^-8</td>
<td>1.22x10^-5</td>
<td>2.89x10^-6</td>
</tr>
</tbody>
</table>

(c) Finite Element Model Geometry. The general layout of the FEM is shown in Figure 15. The pavement cross section had a cross slope of 2.5% and total width of 7.3 m (2-lanes). The pavement cross section consisted of 114.3 mm asphalt layer followed by 241.3 mm base layer placed on the top of subgrade. The natural ground was extended laterally 11 m beyond the side ditch on each side to be consistent with field conditions (Ariza and Birgisson 2002). For this local road, the subgrade had the same properties as the natural existing soil. The side ditches had bottom width of 1.5 m and 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 width of 2.54 cm and depth of 5.71 cm. In the sealed section, these gaps were closed forming impermeable regions.

(d) 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.
(e) **Boundary Conditions.** Boundary conditions assigned for the steady-state analysis were as follows, see Figure 15:

- 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 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 15. Model Geometry and Boundary Conditions of the Steady-State Analysis](image)

The boundary conditions assigned for the transient analyses were as follows, see Figure 16:

- Similar drainage conditions were assigned at the bottom corners of the model, as previously mentioned.
- Time-dependent temperature, shown in Figure 17 a, was assigned at 10 cm below the pavement surface.
- Boundary condition for the Land Climate Interaction (LCI) was assigned along the asphalt 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 17 (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 (Wilson 1990).

![Figure 16. Boundary Conditions of the Transient Analyses](image)

### 3.7.2. 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, 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 including wide range of asphalt permeabilities, rain intensities, Ground Water Table (GWT) depths, air temperatures, and relative humidity to develop a framework that can be deployed for different asphalt mixes and in different climatic regions.
Figure 17. Soil Temperature and Climatic Conditions for Chase District from 4/20/2017 to 5/16/2018
3.8. Develop an Enhanced Decision Making Tool

Since pavements vary in their behavior and potential needs depending on type of pavement structure, groundwater table level, climate, traffic, and other factors; the success of crack sealing was not expected to be the same for all encountered conditions. Instead, the benefits and cost-effectiveness of this treatment was more justified 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 determines whether crack sealing is an effective maintenance treatment to be applied to an existing AC overlay based on the specific road conditions. In this 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 crack sealing application; and
3. cost effectiveness of crack sealing.

Furthermore, the developed tool could be used to determine the optimal timing, in terms of RCI of crack sealing. In order to make this tool time-efficient and easy to use, it was developed using micros in Microsoft Excel.
CHAPTER 4. STATEWIDE SURVEY AND DATA COLLECTION

This chapter provides the results of a statewide comprehensive survey that was conducted to gather information from districts in Louisiana as related to the current practices in using crack sealants and their effectiveness as a preventive maintenance activity. This chapter also provides a full description of the identified candidate crack sealing and AC overlay projects and collected data that were used in the analysis.

4.1. Survey Overview

Figure 18 shows the districts that responded to the survey. In total, 6 out of the 9 districts responded to the survey, namely, districts 4, 5, 7, 8, 58, and 61.

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 is selected. To expedite
the response to the survey, the survey questionnaire focused on seven main questions as follows:

1. Do you currently use crack sealing in your district/city/parish?
2. Do you keep record (construction files) of the crack-sealed roads?
3. What is the overall budget spent in 2014, 2015, or 2016 on crack sealing?
4. Do you select the roads to be treated with crack sealing based on pavement conditions (PMS data) through a pre-set schedule, visual inspection?
5. Do you perform crack sealing in-house or through external contracts?
6. Do you perform any Quality Assurance for acceptance of installed crack sealing?

4.2. Survey Results
Respondents were queried whether they currently use crack sealing in their districts and whether they keep records (construction files) of the treated roads. Results indicated that crack sealing is commonly used in four out of the six districts. The survey results also indicated that most of the districts that use crack sealing keep records of their treated roads.

Furthermore, the survey respondents were queried on the overall budget spent in 2014, 2015, or 2016 on crack sealing. Table 4 presents the annual budget spend by each district on crack sealing. Although crack sealing is commonly used in most of the districts, it was assigned the lowest average annual budget due to its relatively low costs.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>District</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Average annual budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crack sealing</td>
<td>4</td>
<td>5</td>
<td>7</td>
<td>8</td>
<td>58</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>211,000</td>
<td>-</td>
<td>-</td>
<td>30,000</td>
<td>30,000</td>
<td>90,333</td>
</tr>
</tbody>
</table>
The survey respondents were queried on the criteria used by districts to select the roads to be treated with crack sealing, namely, (1) based on pavement conditions (PMS data) only, (2) based on visual inspection only, and (3) based on both. The results indicated that 75% of the districts that use crack sealing apply this treatment based on visual inspection only, while only 25% apply this treatment based on both, visual inspection, and PMS data.

Districts were queried on the method they use to accomplish crack sealing, namely, (1) in-house application, (2) through external contracts, or (3) through both. The survey results indicated that all the districts that use crack sealing perform in-house application. This is possibly because change orders can be handled more efficiently with in-house crews, and policy decisions can be made and communicated easier with in-house crews. It is worthy to note that one district that frequently uses crack sealing associates external contracts with in-house application to provide more flexibility in the application process.

Districts were queried whether they perform Quality Assurance for acceptance of installed crack sealing. The survey results indicated that only 50% of the districts that use crack sealing perform Quality Assurance in the form of visual inspection.

The results of this survey were crucial to accomplish the following tasks and achieve the objectives of this study. For instance, recognizing that all the districts that use crack sealing perform in-house application, guided the research team to the appropriate database for data collection. In Louisiana, in-house applications are captured via the Maintenance Management System’s work orders, while maintenance treatments applied using external contracts are recorded in the PMS databases. Furthermore, recognizing that crack sealing is usually applied in Louisiana based only on visual inspection, helped the research team determine the reasons behind several problems encountered with this treatment and address these problems.
4.3. Data Collection Process

LaDOTD databases were mined for preliminary identification of the crack sealing 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 investigated to determine the exact date and location of crack sealing and AC overlay, see examples in Figures 19 and 20. It is worthy to note that unsealed data points (log-miles) were selected before and/or after the selected crack-sealed data points for comparative evaluation.

Figure 19. Pavement Section Before (left) and after (right) Crack Sealing

Figure 20. Pavement Section Before (left) and after (right) AC Overlay

To provide an accurate presentation of the effect of crack sealing, the analysis was conducted for every log-mile, which was considered as a single data point. While in the analysis of AC overlays, each project was considered as a single data point and a single average value was calculated over the project limits for each index and for each collection year.
Once the data points were identified for crack sealing and AC overlay, ADT, type of original pavement, thickness of original pavement, treatment costs, and performance data were collected for these points. In specific, RCI and RFI were collected for crack–sealed data points, while PCI, RCI, RTI, and RFI were collected for AC overlay data points. Eventually, for each data point, collected indices were visualized and analyzed for final selection of the data points that would be considered in this research. For any data point to be included in the analysis, it had to meet all the following acceptance criteria:

- Has at least one index before treatment application;
- Has at least three indices after the treatment application; and
- Exhibit negative gain in distress along the treatment service life.

### 4.4. Final Data Sets

Tables 5 and 6 summarize the final total number of data points considered in this study.

**Table 5. Size and Description of Data Sets Used in the Analysis of Crack Sealing**

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

¹Log miles (control sections)
Table 6. Summary of Control Sections and Data Points Used in the Analysis of AC overlay.

<table>
<thead>
<tr>
<th>Index</th>
<th>Data Set</th>
<th>Control sections</th>
<th>Data points</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCI</td>
<td>8</td>
<td>141</td>
<td>141</td>
</tr>
<tr>
<td>RCI</td>
<td>8</td>
<td>141</td>
<td>141</td>
</tr>
<tr>
<td>RFI</td>
<td>8</td>
<td>141</td>
<td>141</td>
</tr>
<tr>
<td>RTI</td>
<td>8</td>
<td>141</td>
<td>141</td>
</tr>
</tbody>
</table>
CHAPTER 5. ANALYSIS AND RESULTS

5.1. Field Performance of AC Overlays

This section presents the results of evaluating the field performance of AC overlays in Louisiana (Mousa et al. 2019a).

5.1.1. Pavement Service Life (PSL) of AC Overlays

The research team calculated the Pavement Service Life (PSL) of AC overlays, in terms of PCI, RCI, RTI, and RFI using Data set 8 in Table 6. 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 LaDOTD (Khattak et al. 2009). 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 21, 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 for 8% of the projects.

![Figure 21. Limiting Distresses in the Analyzed Projects](image)

For all projects in Data Set 8, 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.
5.1.2. Factors Affecting the PSL of AC Overlays

Figure 22 presents the average PSL categorized based on the pretreatment pavement conditions (condition indices before AC overlay application). The general trend in Figure 22 indicates that longer PSL is achieved with better pretreatment pavement conditions.

![Figure 22. Relationship between Average PSL and Pretreatment Pavement Conditions](image)

When the PSL for different projects was plotted against ADT, no clear trend was observed possibly because the projects had different overlay thicknesses and pretreatment pavement conditions, which seemed to be the most significant factors in determining 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 23 (a, b, and c). In this dissertation, the term PCI refers to the last PCI collected before AC overlay application.

As shown in Figure 23, 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 with similar climatic conditions to Louisiana (Ping and He 1998). 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 23 d. As expected, higher PSL was achieved for higher overlay thicknesses.

![Figure 23. (a), (b), and (c) Average PSL versus PCI for Different Overlay Thicknesses. (d) Average PSL versus Overlay Thickness under High Traffic Level.](image)

Since the overlay thickness primarily affects the PSL of AC overlays, the research team classified all the projects in Data Set 8 in Table 6 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 7. This table could be used in Louisiana to predict the AC overlay PSL knowing the AC overlay thickness. This is important during the cost-benefit analysis of crack sealing applied on AC overlays.
Table 7. Lower and Upper 95% Confidence Intervals and Average Overlay PSL (in years) for Difference Thickness Classes

<table>
<thead>
<tr>
<th>Descriptive statistics</th>
<th>AC overlay thickness class</th>
<th>&lt;=2 inch</th>
<th>&gt;2 inch to &lt;=3 inch</th>
<th>&gt;3 inch to &lt;=4 inch</th>
<th>&gt;4 inch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td></td>
<td>15.5</td>
<td>16.4</td>
<td>17.2</td>
<td>19.8</td>
</tr>
<tr>
<td>Upper interval</td>
<td></td>
<td>16.9</td>
<td>18.3</td>
<td>18.7</td>
<td>27.0</td>
</tr>
<tr>
<td>Lower interval</td>
<td></td>
<td>14.0</td>
<td>14.4</td>
<td>15.7</td>
<td>12.5</td>
</tr>
</tbody>
</table>

5.2. Field Performance of Crack Sealing

To quantify the benefits of crack sealing, the PJ, APG, PSL*, and ΔPSL were computed and evaluated (Mousa et al. 2018). In this dissertation, the term RCI refers to the last RCI collected before sealing date (pre-treatment random cracking index). Furthermore, ΔRCI refers to the difference between RCI at sealed and unsealed log miles (sealed-unsealed) at time (i).

5.2.1. Performance Jump (PJ)

The Performance Jump (PJ) for RCI and RFI was calculated using Data Sets 1 and 6, respectively, in Table 5. 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 significant immediate impact on RCI as shown in Figure 24. On the other hand, for the RFI, only 22% of the 306 log miles had positive PJ with mean value of 2.3 ± 2. This indicates that crack sealing has minor or negligible immediate impact on roughness as suggested by other studies (Fang et al. 2003; Ong et al. 2010). Therefore, the analysis of the long-term field performance of crack sealing in the following sections was limited to RCI.
5.2.2. Average Performance Gain (APG)

Data Set 2 in Table 5 was used to calculate the APG. Figure 25 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 supported 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.
5.2.3. Increase in Pavement Service Life (PSL*)

Data Set 3 in Table 5 was used to calculate evaluate the effect of crack sealing in extending the PSL when compared with the untreated segments through calculating PSL*. First, the research team selected threshold 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 RCI of 69 was assumed to match the pavement-rating scheme used by LaDOTD for other cracking distresses (Khattak et al. 2009). Second, the PSL for sealed and unsealed log-mils 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 sealed segment to obtain PSL*.

Figure 26 presents PSL* and ΔRCI before sealing (ΔRCI) for each control section. For most of the sections, the sealed segment experienced an average PSL* of two years more than the unsealed segment, which is comparable with other studies (Ponniah and Kennepohl 1996). 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 (Caltrans 2003); therefore, no positive PSL* was experienced.
5.2.4. 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 5. In this analysis, RCI performance curves were plotted before and after crack sealing and ΔPSL was calculated using Equations 5, 6, and 7. Figure 27 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 is achieved after crack sealing, and therefore, the extension in the PSL was set to zero. As shown in Figure 27, both pavement types followed similar trends such that ΔPSL had negative values for RCI more than 90. 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 relatively 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, probably 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 5. Figure 28 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 (Smith and Romine 1999).

![Figure 27. ΔPSL versus RCI for Data Set 4](image)
5.2.5. 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 8. 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>
<thead>
<tr>
<th>Variables</th>
<th>t-value</th>
<th>P-value</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>7.36</td>
<td>&lt; 0.001</td>
<td>Significant</td>
</tr>
<tr>
<td>RCI</td>
<td>-9.56</td>
<td>&lt; 0.001</td>
<td>Significant</td>
</tr>
<tr>
<td>Pavement age at sealing date</td>
<td>0.23</td>
<td>0.82</td>
<td>Not Significant</td>
</tr>
<tr>
<td>ADT</td>
<td>4.39</td>
<td>&lt; 0.001</td>
<td>Significant</td>
</tr>
<tr>
<td>pavement type</td>
<td>-5.47</td>
<td>&lt; 0.001</td>
<td>Significant</td>
</tr>
</tbody>
</table>

Table 8. Results of Analysis of Variance (ANOVA)

For each pavement type, 80% of the data was used to fit the model and 20% 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:

(a) Flexible Pavement:

\[ ΔPSL = (-77.454 \times RCI) + (0.972 \times (RCI)^2) + (-0.004 \times (RCI)^3) + (-2.745E^{-04} \times ADT) + (-1.751E^{-07} \times ADT^2) + (1.566E^{-11} \times ADT^3) + 2057.898 \]

Where ADT ≤ 11,100, and 70 < RCI < 100

(b) Composite Pavement:

\[ ΔPSL = (-45.780 \times RCI) + (0.603 \times (RCI)^2) + (-0.003 \times (RCI)^3) + (4.35E^{-04} \times ADT) + (1.391E^{-07} \times ADT^2) + (-1.1E^{-11} \times ADT^3) + 1157.696 \]

Where ADT ≤ 15,100, and 70 < RCI < 100

Figure 29 (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 R² and root mean square error (RMSE) shown in the figures. For the flexible pavement, the R² and RMSE were almost 0.9 and 2.3 years, respectively, while for the composite pavement, the R² 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 30. It is noted that the developed model follows the same trends shown in Figures 27 and 28 based on the measured data.
Figure 29. Predicted ΔPSL versus Actual ΔPSL Using Fitting Data for (a) Flexible Pavements and (b) Composite Pavements

Figure 30. Predicted ΔPSL versus RCI for Flexible Pavements under Different ADT
5.2.6. Illustrative Applications of Predictive Model

During 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 could 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 9 and 10 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 9 and 10, 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 9. Illustrative Application of the Proposed Model for Flexible Pavements

<table>
<thead>
<tr>
<th>RCI</th>
<th>ADT</th>
<th>Actual ΔPSL</th>
<th>Predicted ΔPSL</th>
<th>RMSE (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>88.77</td>
<td>3000</td>
<td>4.34</td>
<td>6.43</td>
<td></td>
</tr>
<tr>
<td>72.93</td>
<td>2600</td>
<td>6.06</td>
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<td>79.77</td>
<td>2600</td>
<td>8.72</td>
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<td>82.27</td>
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<td>74.66</td>
<td>2600</td>
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<td>-9.25</td>
<td>-8.56</td>
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<td>93.00</td>
<td>6000.00</td>
<td>-12.70</td>
<td>-1.24</td>
<td></td>
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<tr>
<td>93.33</td>
<td>5500</td>
<td>-0.03</td>
<td>-1.48</td>
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</tr>
<tr>
<td>95.84</td>
<td>5500</td>
<td>-3.19</td>
<td>-7.36</td>
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</tbody>
</table>
Table 10. Illustrative Application of the Proposed Model for Composite Pavements

<table>
<thead>
<tr>
<th>RCI</th>
<th>ADT</th>
<th>Actual ΔPSL</th>
<th>Predicted ΔPSL</th>
<th>RMSE (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>81.94</td>
<td>15100</td>
<td>4.988</td>
<td>2.95</td>
<td></td>
</tr>
<tr>
<td>83.22</td>
<td>15100</td>
<td>2.71</td>
<td>2.73</td>
<td></td>
</tr>
<tr>
<td>84.27</td>
<td>15100</td>
<td>2.23</td>
<td>2.42</td>
<td></td>
</tr>
<tr>
<td>84.68</td>
<td>2300</td>
<td>3.59</td>
<td>3.45</td>
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</tr>
<tr>
<td>75.44</td>
<td>320</td>
<td>5.05</td>
<td>2.20</td>
<td></td>
</tr>
<tr>
<td>73.51</td>
<td>370</td>
<td>2.16</td>
<td>1.99</td>
<td></td>
</tr>
<tr>
<td>76.44</td>
<td>370</td>
<td>1.85</td>
<td>2.38</td>
<td></td>
</tr>
<tr>
<td>77.65</td>
<td>370</td>
<td>1.36</td>
<td>2.55</td>
<td></td>
</tr>
<tr>
<td>76.14</td>
<td>370</td>
<td>1.37</td>
<td>2.33</td>
<td></td>
</tr>
<tr>
<td>72.4</td>
<td>370</td>
<td>2.5</td>
<td>1.91</td>
<td></td>
</tr>
<tr>
<td>70.32</td>
<td>370</td>
<td>1.86</td>
<td>1.99</td>
<td></td>
</tr>
<tr>
<td>76.16</td>
<td>370</td>
<td>1.06</td>
<td>2.33</td>
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<td>72.75</td>
<td>370</td>
<td>2.6</td>
<td>1.93</td>
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<td>73.83</td>
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<td>370</td>
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<td>-5.11</td>
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<tr>
<td>96.65</td>
<td>3700</td>
<td>-8.02</td>
<td>-14.24</td>
<td></td>
</tr>
</tbody>
</table>

5.3. Cost Benefit Analysis

This section outlines the cost-benefit analysis of applying crack sealing to AC overlays in Louisiana (Mousa et al. 2019b). This section also provides the optimal timing of crack sealing application. The EAC, B/C, and CE were calculated for each data point in Data Set 7 in Table 5. The computed EAC, B/C, and CE was then categorized based on the pre-treatment pavement conditions (RCI) and the average was calculated. Since previous tasks indicated that crack sealing applied to pavements in a relatively good condition (RCI greater than or equal 90) exhibit no or negligible benefits, the RCI in this section was grouped as follows: (a) <77, (b) 77-80, (c) 81-84, and (d) 85-89.
5.3.1. Equivalent Annual Cost (EAC)

Figure 31 shows the average EAC for crack sealing versus RCI. As shown, the lowest EAC was achieved for RCI group “81-84”. This 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.

5.3.2. Benefit Cost Ratio (B/C)

A sample calculation of the B/C for one of the data points is provided in the Appendix. Figure 32 shows the average B/C for crack sealing versus the pretreatment pavement conditions. Since the B/C for all the groups was greater than one, it could be concluded that crack sealing is cost-effective regardless the pretreatment pavement condition. 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.
5.3.3. Cost Effectiveness (CE)

Figure 33 presents the average CE for crack sealing versus the RCI. As shown, the highest CE (most cost-effective scenario) was obtained for the “85-89” group and decreased towards lower RCI groups.

5.3.4. Model Development for the Treatment Net Benefits (TNB)

The positive Treatment Net Benefits (TNB) calculated in the previous section; which were used to compute the CE; see Equation 10, 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 11. 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 11. Results of ANOVA

<table>
<thead>
<tr>
<th>Variables</th>
<th>P-value</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCI</td>
<td>&lt; 0.001</td>
<td>Significant</td>
</tr>
<tr>
<td>Pavement type</td>
<td>0.6</td>
<td>Not Significant</td>
</tr>
<tr>
<td>A</td>
<td>&lt; 0.001</td>
<td>Significant</td>
</tr>
<tr>
<td>ADT</td>
<td>&lt; 0.001</td>
<td>Significant</td>
</tr>
<tr>
<td>ΔPSL</td>
<td>&lt; 0.001</td>
<td>Significant</td>
</tr>
</tbody>
</table>

A total of 117 data points was 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:

\[
\text{TNB} = (40.76\times\text{RCI}) + (-0.504\times(\text{RCI})^2) + (0.00217683805844751\times(\text{RCI})^3) + (-175.9\times\text{A}) + (22\times\text{A}^2) + (-0.8813969492287229\times\text{A}^3) + (0.009\times\text{ADT}) + (-1.466\times10^{-6}\times\text{ADT}^2) + (5.1\times10^{-11}\times\text{ADT}^3) + (21.4\times\Delta\text{PSL}) + (-0.971\times\Delta\text{PSL}^2) + (0.03013630001\times\Delta\text{PSL}^3) + (-703.523) \]  

Where ADT<15,100, and 70 < RCI <100. Figures 34 and 35 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 R² and RMSE shown in the figures. For the fitting data, the R² and RMSE were 0.90 and 20.3, respectively, while for the test data, the R² and RMSE were approximately 0.83 and 27.1, respectively.
This section presents the results of the laboratory testing that was conducted during the experimental program. These results were crucial in the finite element modeling of crack sealing in the following section.
5.4.1. Lottman Test

The results of Lottman test for groups B, C, D, and E are presented in Figure 36. As shown in this figure, the critical soaking time \( t_s \) corresponding to a TSR of 80% was almost 1.3 days. This value would be used in the following chapter to assist in evaluating the effect of crack sealing on moisture damage.

![Figure 36. Results of the Lottman Test](image)

5.4.2. 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 \( K_{saf} \) for the three cores was measured to be \( 3.45 \times 10^{-8} \) m/s.

5.5. Effect of Crack Sealing on Moisture Damage

This section presents the results of the finite element model and its application to evaluate potential moisture damage after crack sealing application (Mousa et al. 2019c).

5.5.1. 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 (Topp et al. 1980). 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 until the predicted VMC was increased to 0.31, which was very close to the field VMC. Figure 37 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 38, showed strong reflections at 0.6 m; these strong reflections are generally due to the GWT (Hengari et al. 2013).

Figure 37. Zero and Negative Pore-Water Pressure Contours for the Steady-State Analysis

Figure 38. GPR Line Scan at Log-mile 1.6
Transient State Analyses

Subgrade sample taken 14 days after the first site visit was 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, 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 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 (Rabab'ah and Liang 2007) and Minnesota (Ariza and Birgisson 2002).

5.5.2. 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 FEM 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 $1.0 \times 10^{-5}$ and $9.2 \times 10^{-8}$ m/s were simulated to include the typical range of permeability of dense-graded asphalt mixes as reported in previous studies (Mallick et al. 2003; Guada and Harvey 2018). Figure 39 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 $1.0 \times 10^{-5}$ and $9.2 \times 10^{-8}$ m/s.
When the AC $K_{sat}$ was $1.0 \times 10^{-5}$ m/s, the crack-tip became fully-saturated after four hours of rain because the water reached the crack tip through the permeable pavement structure. When the AC $K_{sat}$ was $9.2 \times 10^{-8}$ 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 almost $2 \times 10^{-6}$ m/s.

Louisiana specifies 19-mm Nominal Maximum Aggregate Size (NMAS) and a lift thickness between 40 and 50 mm for wearing course mixtures (Mohammad et al. 2003). A recent study in Louisiana indicated that the permeability of such mixes vary widely between $6.8 \times 10^{-5}$ m/s and $1 \times 10^{-8}$ 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 (Mohammad et al. 2003):

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

(53)

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 39. 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 model considering the following conditions:

- \( K_{\text{critical}} \) of \( 2 \times 10^{-6} \) 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 reported along the three days as shown in Figure 40. 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 \( K_{\text{critical}} \). 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 described in the previous section. It is worthy to note that the initial saturation values (in Figure 40) 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 (Acimovic et al. 2007) in Colorado found that pavement failure on a recent Stone Matrix Asphalt (SMA) overlay was because the milled surface was exposed to about 7.5 inch of precipitation during the months of planning and paving. When the SMA overlay was placed, it acted as a moisture sealant where moisture was entrapped leading to asphalt failure.

![Figure 40. Saturation versus Time for the Crack-Sealed Model at Different GWT Depth](image)

**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. 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:

- $K_{\text{critical}}$ of $2 \times 10^{-6}$ 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 ($t_{\text{critical}}$) was calculated as follows:

$$t_{\text{critical}} = t_x + t_y + t_z$$  \hspace{1cm} (54)

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 $t_{\text{critical}}$ values were grouped by GWT, H, T and R and the average values were calculated for each combination. As shown in Figure 41 (a and b), $t_{\text{critical}}$ was almost constant for different values of T and R. On the other hand, $t_{\text{critical}}$ varied significantly with different GWT and H, see Figure 41 c. Based on this figure, the average $t_{\text{critical}}$ 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 41 c, under all the other conditions, moisture damage may occur in the unsealed section due to prolonged exposure to water.
Figure 41. $t_{\text{critical}}$ for the Unsealed Section at Different (a) Air Temperature, (b) Rain Intensity, and (c) GWT and Air Relative Humidity.
5.5.3. 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 \( t_{\text{critical}} \) for the unsealed section. This was conducted by constructing a correlation matrix for the FEM input parameters and output results. A summary of this correlation is presented in Table 12. The air relative humidity (H) and GWT showed significant correlations with \( t_{\text{critical}} \) 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 41.

<table>
<thead>
<tr>
<th>FE Model Input Parameters</th>
<th>Statistical Measures</th>
<th>FE Model Output (( t_{\text{critical}} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWT</td>
<td>Pearson Correlation</td>
<td>-.330**</td>
</tr>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td>.000</td>
</tr>
<tr>
<td>T</td>
<td>Pearson Correlation</td>
<td>-.028</td>
</tr>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td>.622</td>
</tr>
<tr>
<td>R</td>
<td>Pearson Correlation</td>
<td>-.106</td>
</tr>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td>.059</td>
</tr>
<tr>
<td>H</td>
<td>Pearson Correlation</td>
<td>.797**</td>
</tr>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td>.000</td>
</tr>
</tbody>
</table>

**. 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 $t_{\text{critical}}$ (254 for fitting and 64 for testing). As previously discussed, two independent variables, namely, GWT and H were considered. However, 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:

$$t_{\text{critical}} = 1.7621 - 0.0491 \text{GWT} + 0.00044 \text{GWT}^2 + 3.2473 \text{RH}^3$$ \hspace{1cm} (55)

$$(R^2 = 84\%)$$

Figure 42 presents the computed $t_{\text{critical}}$ from the FEM and using Equation 54. The comparison shows that $t_{\text{critical}}$ was predicted with an acceptable level of accuracy as indicated by the $R^2$ and RMSE shown in Figure 42. The proposed regression model was plotted for different GWT and H; see Figure 43. It is noted that the developed model follows the same trends shown in Figure 41c based on the finite element analysis.
5.5.4. Illustrative Application of the Regression Model

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

- **Step 1:** To ensure that \( t_{\text{critical}} \) for the sealed section will be zero, check that the hydraulic conductivity of the original asphalt mix is less than or equal \( 2 \times 10^{-6} \) m/s using common field or laboratory devices (Awadalla 2015) or using Equation 53 knowing the lift thickness, air voids and gradation.

- **Step 2:** Use Equation 55 or Figure 43 to predict \( t_{\text{critical}} \) for the unsealed section based on actual data of GWT and average air relative humidity (H) for a given project; and

- **Step 3:** If \( t_{\text{critical}} \) 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 \( 3.5 \times 10^{-8} \) 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 54 to predict $t_{\text{critical}}$ for the unsealed section (3.0 days).

• **Step 3:** Since $t_{\text{critical}}$ 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 44. 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.

![Figure 44. Field Cores Extracted from the Test Section during the Final Site Visit](image-url)
CHAPTER 6. ENHANCED DECISION MAKING TOOL

This chapter presents the enhanced decision making tool that was developed to determine whether crack sealing is an effective maintenance treatment to be applied to an existing AC overlay based on the specific road conditions. In this process, three key criteria were considered as follows:

1. the ability of crack sealing to address surface distresses in the existing overlay, such as, surface cracks, rutting, and roughness;
2. potential subsurface moisture damage as a result of crack sealing application; and
3. cost effectiveness of crack sealing.

Furthermore, the developed tool could be used to determine the optimal timing, in terms of RCI, of crack sealing. In order to make this tool time-efficient and easy to use, the tool was developed using micros in Microsoft Excel. Once this tool is initiated, 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 shown order; and one final button for saving changes. Pressing the first button (Step 1 button), will transfer the user from the Master Sheet to a new worksheet, namely, Step 1 worksheet, that need to be viewed. After that, the user should press the “Return to Master Sheet” button at the end of this worksheet to return to the Master Sheet and complete Steps 2 to 7 similarly. It is worthy to note 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 section provides in-depth discussion of the seven key buttons in the Master Sheet.

6.1. Step 1: Go to Instructions

This button transfers the user from the Master Sheet to Step 1 worksheet which provides instructions to the user to go through before using this tool.
6.2. 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 (Figure 45) that presents the definitions of the years that are included in this tool. In specific, 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 crack sealing is planned to be applied. It is worthy to note 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. To avoid any 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, the user should input the expected ADT when crack sealing is applied; i.e. at year C. The input data should be between 1,200 and 11,100 vehicles per day. Eventually, the user should input the value of the discount rate between 3% and 6%.

![Figure 45. Illustration of Years’ Definitions in the Input Data](image)

6.3. Step 3: Enter Crack Sealing Unit Costs

This button 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 at Year C. Since this value varies significantly from year to another, the spreadsheet does not provide maximum and minimum values for this input. Instead, the maximum and minimum values
are set 9999999 and 0, respectively, just to avoid any errors. Yet, for the user’s convenience, typical unit costs of crack sealing are provided at specific years. For example, it is provided that the unit cost of crack sealing in 2017 was $10,296/lane-mile.

6.4. Step 4: Enter Existing AC Overlay Data

This button 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 crack sealing, 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 obtain this value easily from historical records. The user should also input the thickness of the existing overlay (in inches) to be between 1 and 6 inches. This value should encompass only the thickness of the existing AC overlay which was applied at Year A not the total AC thickness. After that, the user should select the type of the existing overlay from a numerical list of 1 and 2, where 1 refers to flexible overlays and 2 refers to composite overlays. A challenging key input required in this category is the hydraulic conductivity or water permeability (in m/s) of the existing AC overlay. For high accuracy, a core should be taken from the existing AC overlay and tested in the lab easily using the quick Falling Head Permeability Test, shown in Figure 14. Otherwise, the user could use the typical values provided in the spreadsheet for dense graded mixes (9.20 E-8 to 1.00 E-5 m/s). Eventually, the user should input the Pavement Condition Index (PCI), Rutting Index (RTI), Roughness Index (RFI), and Random Cracking Index (RCI) of the existing overlay at Year C which could be easily obtained from the PMS database.

6.5. Step 5: Go to Results of Surface Distresses Analysis

This button transfers the user from the Master Sheet to Step 5 worksheet. This worksheet is shown in Figure 46 and determines whether crack sealing is appropriate to
address the existing surface distresses in the pavement without considering the cost-effectiveness of crack sealing or its stripping potential. This selection is solely based on the RCI, RTI and RFI of the existing overlay at Year C which are provided by the user in Step 4.

Figure 46. Output Worksheet in Step 5

6.6. Step 6: Go to Subsurface Moisture Damage Results

This button transfers the user from the Master Sheet to Step 6 worksheet. This worksheet is shown in Figure 47 and predicts whether moisture damage will occur after crack sealing given that crack sealing is applied after extended dry periods. It is worthy to note that this selection depends only on the hydraulic conductivity provided by the user in Step 4.
6.7. Step 7: Go to Performance and Cost Benefit Results

This button transfers the user from the Master Sheet to Step 7 worksheet. This worksheet presents the ΔPSL, EAC, B/C and CE for crack sealing. These computations are based on most of the input data provided by the user, specifically the RCI and PCI of the existing AC overlay. While ΔPSL reflects only the treatment performance without considering the relevant costs, EAC, B/C and CE reflect the cost effectiveness of crack sealing.

It is worthy to note that the user should consider the results of the three worksheets in Steps 5 to 7 simultaneously before taking a final decision regarding the appropriateness of crack sealing for a specific project. For example, crack sealing may be cost effective 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 determine the appropriateness of crack sealing for a specific project, this tool could be used to determine the optimal timing of crack sealing. This could be achieved through changing the RCI in Step 4 and tracking the resulting EAC, B/C and CE in Step 7. The RCI that results in the lowest EAC and highest B/C or CE is the optimal timing of crack sealing.
CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

The objective of this dissertation was twofold. First, this study quantified the benefits of using crack sealing with respect to its ability to provide immediate benefits 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. 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 through evaluating its cost effectiveness using common economic measures. Based on the results of the study and the conducted cost analysis, the following key conclusions were drawn:

7.1. LADOTD State-of-the-Practice

- Crack sealing is one of the most common preventive maintenance treatments used in Louisiana.
- As of 2016, the average annual budget per district spent on crack sealing was $90,333.
- Crack sealing is usually applied solely based on visual inspection without considering pavement conditions.

7.2. Pavement Service Life of AC Overlays

- The most common surface distress in AC overlays in Louisiana is random cracking followed by rutting.
- For AC overlays in Louisiana, 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.
• The PSL of AC overlays primarily depends on the pre-treatment pavement condition (pavement condition before overlay application) and the AC overlay thickness.

7.3. 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 selected 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 R² and RMSE. 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.

7.4. 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.

7.5. 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 2x10⁻⁶ m/s).
• Crack sealing should be applied after an extended dry period after measuring the initial saturation of the original pavement 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 due to the accelerated drainage by evaporation.

7.6. Development of an Enhanced Decision Making Tool

Based on the aforementioned conclusions, a user-friendly tool in the form of a spreadsheet was designed that could be used by state agencies during planning for crack sealing. 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 determine whether crack sealing is an effective maintenance treatment to be applied to an existing AC overlay based on the specific road conditions.

7.7. Recommendations

Based on the findings of this study, it is recommended to use the developed tool before applying crack sealing. For a specific project, this tool will determine whether crack sealing is an effective maintenance treatment to be applied to an existing AC overlay. The tool will also provide the optimal timing of crack sealing. Future activities should also consider the following important research needs:

• 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.
REFERENCES


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APPENDIX. 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:

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

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

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

\[
\frac{B}{C} = \frac{44,348 - 39,792}{1,061} = 4.29
\]
VITA

Momen R. Mousa was born in San Luis Obispo, California, USA, on September 17, 1990. He is a Ph.D. student in Louisiana State University, who received both his B.S. and M.S. degrees in civil engineering from Cairo University, Egypt, in 2012 and 2015, respectively. From 2012 to 2016 and prior to joining the civil engineering department at LSU, he worked as Highway and Traffic Engineer at Civil and Environmental Engineering Group (CEEG) and participated in many international projects. He also served as a teaching assistant in the German University in Cairo (GUC). Eng. Mousa’s particular research interests encompass asphaltic materials, pavement analysis and evaluation, and sustainable infrastructure. He anticipates to receive his Doctor of Philosophy degree in civil engineering in August 2019 from Louisiana State University.