Final Report

Investigation of Reflective Cracking Mitigation Techniques

FDOT Contract No.: BDK78-977-17

Prepared by:

Boo Hyun Nam, Ph.D.
Faculty Principal Investigator

Behnam Golestani, M.S.
Graduate Research Assistant

Mehdi Noori, M.S.
Graduate Research Assistant

Omer Tatari, Ph.D.
Faculty Co-Investigator

And

Jinwoo An, M.S.
Graduate Research Assistant

Department of Civil, Environmental, and Construction Engineering
University of Central Florida
4000 Central Florida Blvd.
Orlando, FL 32816-2450

In cooperation with

Office of Materials
State of Florida Department of Transportation
605 Suwannee Street, MS30
Tallahassee, FL 32399-0450

March 2014

DISCLAIMER

UNIT CONVERSION

To convert from	To	Multiply by
mm	cm	0.1
	m	0.01
	in.	0.03937
	ft.	0.003281
mg	g	0.001
	kg	1×10^{-6}
	oz	0.000035
	lb	2.2046×10^{-6}
ml	l	0.001
	cm^3	1
	m^3	1×10^{-6}
	$in.^3$	0.061024
	$ft.^3$	0.000035
	gal	0.000264
	oz	0.033814
Pa	hPa	0.01
	kPa	0.001
	MPa	1×10^{-6}
	kgf/cm^2	0.00001
	psi	0.000145

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Investigation of Reflective Cracking Mitigation Techniques		5. Report Date March 2014 6. Performing Organization Code
7. Author(s) BooHyun Nam, Behnam Golestani, Mehdi Noori, Omer Tatari, and Jinwoo An		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Central Florida 4000 Central Florida Blvd. Orlando, FL 32816-2450		10. Work Unit No. (TRAIS) 11. Contract or Grant No. BDK 78-977-17
12. Sponsoring Agency Name and Address Office of Materials State of Florida Department of Transportation 605 Suwannee Street, MS30 Tallahassee, FL 32399-0450		13. Type of Report and Period Covered Draft Final Report July 2012 to February 2014 14. Sponsoring Agency Code

15. Supplementary Notes
Mr. James Greene of the State Material Office at the Florida Department of Transportation served as the project manager for this project.

16. Abstract
In the state of Florida, an asphalt rubber membrane interlayer (ARMI) has been commonly used as a reflective cracking (RC) mitigation method, but inconsistent performance of an ARMI has been observed in the field. Moreover, the Heavy Vehicle Simulator (HVS) study illustrated that an ARMI contributes to instability rutting. Therefore, finding alternatives to mitigate RC, considering Florida's climate and rehabilitation practices was inevitable. Considering Florida's road conditions, the focus of this research was placed on the evaluation of RC mitigation methods for asphalt concrete (AC) overlays over flexible pavements. Two primary objectives of this research are: (1) to identify structurally suitable RC mitigation methods and (2) to determine top RC mitigation methods regarding cost, performance, and other design variables (e.g., recyclability, design and construction familiarity, proprietary product). The research methodology has included an extensive literature review, survey, personal interviews, numerical simulation (finite element analysis), life cycle cost analysis (LCCA), and multi-criteria decision making (MCDM) analysis. This research methodology was aimed at: (1) understanding the current practices of RC mitigation management across the nation; (2) finding the exact mechanism based on stress/strain analyses; (3) evaluating performance of existing RC mitigation methods; and (4) identifying the most "cost-performance" effective RC mitigation method. Based on the analyses, it is concluded that increasing the thickness of mill and inlay/overlay, followed by fabric, is the most effective method.

17. Key Word Reflective cracking mitigation, finite element analysis, life cycle cost analysis (LCCA), multi criteria decision making (MCDM) analysis	18. Distribution Statement No restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.	153	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGEMENTS

This research was funded by the Research and Development Office of the Florida Department of Transportation (FDOT). The authors also thank the Project Manager and Research Panel for their guidance and sharing their experiences and knowledge, which were valuable inputs for the analyses in this study.

EXECUTIVE SUMMARY

In order to mitigate the reflective cracking problem, approximately 20 years ago, the Florida Department of Transportation (FDOT) began using an asphalt rubber membrane interlayer (ARMI) on rehabilitation projects where the existing cracks could not be entirely removed. Generally, FDOT's ARMI studies have shown that reflection cracking (RC) could be delayed to some extent when a pavement system with the ARMI is properly designed and constructed. However, it is still questionable whether the ARMI is the most effective method with respect to cost and performance. The ability of an ARMI to mitigate reflection cracking has been evaluated through several experimental and long-term monitoring projects. Varied performance of an ARMI has been reported from the Districts. In addition, an accelerated pavement testing (APT) study conducted by the State Materials Office (SMO) demonstrated that an ARMI contributes to instability rutting when subjected to slow and heavy loads and typical summer temperatures. Therefore, due to the inconsistent performance of an ARMI, finding alternatives to mitigate RC, considering Florida's road and climate conditions, was necessary.

The objectives of this study were: (1) to identify the structurally suitable RC mitigation methods for asphalt concrete (AC) overlays over flexible pavements considering Florida's climate and road conditions; and (2) to identify the top RC mitigation methods with respect to cost, performance, and other factors such as recyclability and design and construction familiarity. To achieve these objectives, the research methodology included an extensive literature review (especially in the U.S.), nationwide and statewide surveys, personal interviews, numerical simulations with finite element model (FEM) analysis, life cycle cost analysis (LCCA), and multi-criteria decision making (MCDM) analysis.

The literature review, survey, and personal interviews were aimed at understanding the RC mechanism and the current practices of RC mitigation management across the country. The survey result showed that the most popular RC mitigation method is an increase of mill and inlay/overlay thickness. Also, a majority of state highway agencies (SHAs) do not currently have an available overlay design method which is specifically for the RC mitigation purpose. Considering inconsistent performance of existing RC mitigation methods, the mill and inlay/overlay option can be the least risky method considering the crack propagation rate of 1 inch/year rule of thumb [1, 6].

The FEM analysis was aimed at understanding the exact mechanism of RC in an AC overlay over a flexible pavement. Most literature has reported the same RC mechanisms for flexible and rigid pavement AC overlays. However, as a major mode of pavement movements, the underlying jointed concrete pavements (JCPs) will create vertical differential movements at joints under wheel loads while the underlying hot-mix asphalt (HMA) will produce bending deformation; thus, fracture modes in the overlay will be somewhat different. In the FEM study, the effects of different cracking conditions (e.g., full-depth, top-down, and bottom-up cracks) and also the influences of different types of RC mitigation methods (mill and inlay, fabric, and ARMI) were evaluated. The results show that a partial-depth top-down crack remaining in the underlying layer after milling causes less damage to the overlay compared to overlays with other cracking conditions. Fabric can be more effective in absorbing tensile and shear stress at the tip of crack; however, due to large deformation in the plane of the fabric, crack development at the bottom of the AC overlay can be a concern under repeated traffic loads. Increased thickness of mill and inlay (or overlay) would be effective in decreasing stress concentration and tensile-strain developed at the bottom of the overlay.

Life Cycle Cost Analysis (LCCA) was conducted to evaluate the cost-performance effectiveness of different RC mitigation methods. The selected RC mitigation methods were (1) fabric (geotextile), (2) chip seal, (3) Strata, (4) interlayer stress-absorbing composite (ISAC), (5) ARMI, (6) cold in-place recycling (CIPR), (7) hot in-place recycling (HIPR), and (8) increased thickness of mill and inlay. Performance variations were large for each method; thus, a new procedure that accounts for the performance compared with the control section was developed and applied to the LCCA analysis. The LCCA results are presented with the range of minimum and maximum performance of each RC mitigation method.

Decision makers, however, will consider other input variables such as performance (life span), recyclability, design and construction familiarity, proprietary product, etc. Thus, the Multi Criteria Decision Making (MCDM) analysis was used to rank the top RC mitigation methods. It is important to note that the weight of each variable can be adjusted depending on knowledge and experiences of pavement engineers (or decision makers). The MCDM analyzed multiple scenarios, for example, budget, performance, recyclability-priority scenarios. As the project budget becomes a higher priority (with higher weight on life cycle cost), fabric becomes more effective. On the other hand, a thicker mill and inlay/overlay would be considered more effective as performance and recyclability become higher priorities.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Background

When hot-mix asphalt (HMA) overlays are placed on jointed and severely cracked rigid or flexible pavements, the underlying cracks can propagate upward into the overlay and result in reflective cracking. These cracks allow water infiltration into the underlying layers and can cause further moisture damage as well as weakening the unbound layers. Previous studies have reported that reflective cracks may propagate vertically through the overlay at a rate of one inch per year [1]. In order to mitigate the reflective cracking problem, approximately 20 years ago, the Florida Department of Transportation (FDOT) began using an asphalt rubber membrane interlayer (ARMI) on rehabilitation projects where the existing cracks could not be entirely removed by milling and for asphalt overlays of concrete pavements. An ARMI is composed of an asphalt rubber binder (ARB-20) applied at a rate of 0.6 to 0.8 gal/ yd^2 followed by an application of a single layer of a No. 6 stone aggregate cover material applied at a rate of 0.26 to 0.33 ft^3/yd^2. The ARB-20 consists of a PG 67-22 asphalt binder modified with a minimum of 20% ground tire rubber. A rubber-tired roller is then used to seat the aggregate into the ARB-20 prior to the placement of an asphalt concrete overlay.

In general, FDOT's ARMI study has shown that reflection cracking can be delayed when a pavement system with an ARMI is properly designed and constructed. However, it is still questionable whether the ARMI is the most effective method with respect to cost and performance. The ability of an ARMI to mitigate reflection cracking has been evaluated through several experimental and long-term monitoring projects. Reflection cracks have been observed as early as one year after the placement of new overlay over concrete pavement on SR-10, Gadsden County Experimental sections with an ARMI have shown similar or greater levels of cracking compared to control sections with No ARMI on SR-2 in Baker County. An accelerated pavement testing (APT) study conducted by the State Materials Office (SMO) demonstrated that an ARMI contributes to instability rutting when subjected to slow and heavy loads and typical summer temperatures.

Therefore, due to the inconsistent performance of an ARMI, an alternative strategy or combination of strategies are necessary to mitigate reflection cracks, considering Florida's road and climate conditions.

1.2. Research Objective

The objectives of the proposed research are: (1) to identify the structurally suitable mitigation methods for flexible pavements considering Florida's special conditions and, (2) to identify the top mitigation methods with respect to cost, performance, and other factors such as recyclability and design and construction familiarity. To achieve these objectives, the research methodology included an extensive literature review (especially in the U.S.), nationwide and statewide survey (including personal interviews), numerical simulations, life cycle cost analysis, and multi-criteria decision making analysis. Findings from these studies were used to identify top reflective cracking mitigation methods suitable for Florida’s conditions and to develop design and construction guidelines for the selected methods.

1.3. Research Scope

This study primarily has focused on (1) understanding of reflective cracking mechanisms in asphalt concrete (AC) overlays under varied environmental and loading conditions, (2) evaluation of the performance of existing reflective cracking mitigation methods, and (3) identification of top mitigation methods considering Florida’s special conditions. The current practices of reflective cracking mitigation management in the state of Florida and across the country have been investigated through extensive literature reviews, personal interviews, and statewide and nationwide surveys. Further investigations to identify the top mitigation methods involved finite element (FE), life cycle cost analysis (LCCA), and Multi-Criteria Decision Making (MCDM) analyses. Considering approximately 98% of state maintained roads are surfaced with asphalt, the research focus has been placed on the AC overlays over flexible pavements.

2. LITERATURE REVIEW

2.1. Introduction

Reflective cracking (RC) in AC overlays occurs at joints or cracks of the underlying pavements. RC can be caused by traffic or environmental load or their combination. Traffic loading causes vertical differential movements at joints/cracks while temperature change causes pavement expansion and contraction. Reflective cracks reduce the service life of in-service roads. Premature cracks in the overlay allow water infiltration, resulting in weakening the load bearing capacity of the base layer and losing bond between aggregates and asphalt binder.

To prevent or retard this phenomenon, different RC mitigation methods have been introduced and used across the country. These RC mitigations have shown varied field performance. In this chapter, an extensive literature review has been conducted to understand (1) mechanisms of RC, (2) currently available RC mitigation methods, (3) case studies showing field performance of the different RC mitigation methods, and (4) affecting parameters of reflective cracking, and (5) cost-benefit studies on each RC mitigation method.

2.2. Reflective Cracking Mechanism

Reflective cracking in AC overlays occur due to mainly the movement of the underlying pavement at joints/cracks and also material deterioration (e.g., aging and moisture damage) in the overlay. Three RC mechanisms have been introduced for overlaid concrete pavements. The three mechanisms are: (1) traffic-induced, (2) thermally-induced due to horizontal movement, and (3) thermally-induced due to slab curling (e.g., slab curling due to temperature differential). In particular, traffic loading induces stress concentration at the crack tip as the result of bending and shearing deformation [2]. Daily pavement temperature change can cause both horizontal movements and curling behavior of concrete slabs. Figure 2.1 shows the three RC mechanisms.

2.2.1. Traffic-induced Cracking

Traffic loading creates vertical differential movements at joints and cracks in the underlying pavements. The vertical differential movement depresses the adjacent slabs, resulting in concentration of shear stress in the overlay. Reflective cracking due to traffic loading is shear-based fatigue distress; thus, the magnitude of the differential movement plays a critical role. Von Quintus (2009) [3] addressed three important parameters which are (1) magnitude of the wheel load, (2) amount of load transfer across the joints or cracks, and (3) differential subgrade support under the slab. RC in this mechanism tends to be bottom-up cracking.

2.2.2. Thermally induced Cracking due to Horizontal Movement

Thermally induced cracking occurs due to the repetition of horizontal movement (expansion and contraction) of the underlying pavement, which is caused by daily temperature changes. Three critical affecting parameters to induce thermally induced cracking are (1) magnitude and range of temperature change, (2) slab geometry, and (3) material properties of the overlay. This thermal cracking is likely to be bottom-up cracking.

2.2.3. Thermally induced Cracking due to PCC Slab Curling

Temperature differential causes slab curling in the underlying Portland cement concrete (PCC) slabs (Figure 2.1). When the PCC slabs curl upward, it results in tensile stress on the surface of the overlay. When the overlay material has lower tensile strength than the tensile stress, cracking is developed at the surface and propagates downward [4].

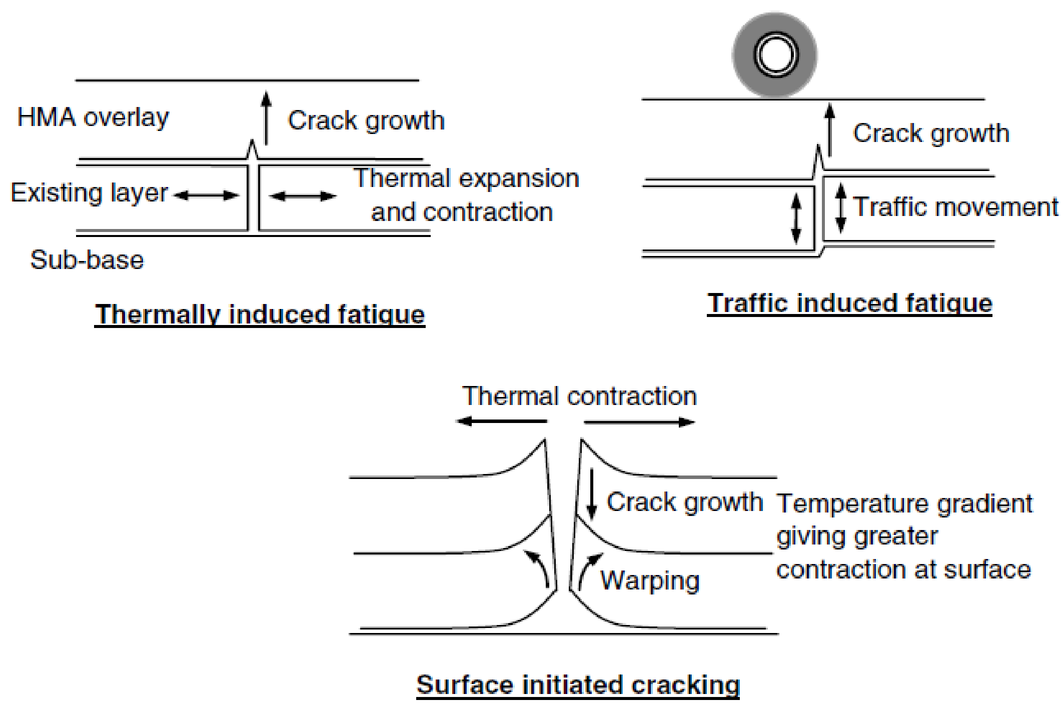


Figure 2.1: Reflective cracking mechanism [5]

2.3. Practical Reflective Cracking (RC) Mitigation Methods

Many RC mitigation methods have been introduced and they are generally categorized as four types of treatments [4]: (1) modification of overlay layer/mixture, (2) treatment of underlying pavement, (3) using an interlayer system, and (4) reinforcement of HMA overlay. Different treatments under each category are described in this section.

2.3.1. Modification of Overlay Layer/Mixture

Modifications of overlay layer involve the improvement of fracture resistance properties of HMA overlay mixture. The modifications of the overlay include utilizing special mixtures in the overlay such as rubber modified asphalt mixtures (AR), polymer modified asphalt (PMA) and stone matrix asphalt (SMA). Increasing the overlay thickness also falls into this category. Thicker HMA overlays produce smaller levels of stress and strain at the crack tips and delay the development of reflective cracking. In addition, thicker overlays take longer time for reflective cracks to propagate through the overlay.

2.3.1.1. Thick HMA Overlay

Increasing the thickness of the HMA overlay reduces the levels of stress and strain developed at the crack tips. On the other hand, a benefit of thicker overlays on rigid pavements is the ability of the HMA to insulate the PCC. Reducing the amount of temperature change and temperature differential can creates less slab curling and slab expansion/contraction. The overlay thickness is determined based on the following four factors [2]: (1) HMA overlay materials, (2) existing pavement condition, (3) climate condition, and (4) traffic loading condition. Thicker overlays can be accompanied with some other treatments such as reinforcement of HMA overlay (e.g., modified asphalt binder or mixture) and introducing stress relief interlayer systems. As a rule of thumb, crack propagation rate in HMA overlays is about 1 inch per year [1, 6]; thus a thicker overlay delays reflective cracking on the surface. In a case study in Georgia [7], the field performance of HMA overlay over PCC was evaluated in six road sections with and without fabrics and also with different overlay thickness.

2.3.1.2. Modified Asphalt Binder/Mixtures

Reflective cracking resistance depends on material properties such as asphalt binder grade, content, and temperature susceptibility. Although using modified asphalt mixtures do not prevent or stop reflective cracking, their applications can reduce the severity of the reflective cracks. The following are three common methods of the modified asphalt binder/mixtures.

- **Low Viscosity Asphalt:** The brittleness of HMA mixture at low temperature causes more susceptibility to cracking. Low viscosity asphalt binder can be used to improve the resistance to reflective cracking. The lower the viscosity of asphalt binder, the less potential of reflective cracking. However, having soft asphalt in the wearing surface will increase potential of bleeding and rutting.

- **Specialty Mixtures:** SMA is a specialty mixture to improve the resistance of rutting and cracking as a wearing surface. The SMA is composed of gap-grade aggregates with fibers and modifiers as well as thicker asphalt films surrounding the aggregates.

- **Modified Asphalt Mixtures.** Asphalt modifications are designed to improve the performance of asphalt mixture at both low and high temperatures. Generally, stiff asphalt at high temperatures and soft asphalt at low temperatures are desirable to avoid rutting and cracking and rutting, respectively. Many laboratory and field studies have shown that the strength of HMA increases with additives such as limestone dust, asbestos fibers, polymer, and rubber. Three examples of the asphalt mixture modification are 1) polymer modified asphalt mixture, 2) rubber-asphalt mixture, and 3) sulfur asphalt mixtures.

2.3.2. Treatments of Existing Pavement

Treatments of the existing pavement are used to either strengthen or weaken and to alter the physical features of the surface layer. These methods remove cracks in the existing pavement surface and adjust the joint condition of PCC slabs. The crack or break and seat and rubblization methods are used in PCC slabs while mill and replace, full-depth reclamation, hot in place recycling, and heater scarification are used in HMA pavements.

2.3.2.1. Crack and Seat (or Break and Seat) for PCC

The crack and seat method produces shorter PCC slabs from 0.6 to 1.8 m (2 to 6 ft) in length. Shorter slabs can reduce the stress concentration at the joints of underlying slabs. Technically, the crack and seat refers to jointed plain concrete pavement (JPCP) while the break and seat refers to jointed reinforced concrete pavement (JRCP). Shorter slabs reduce horizontal movements due to daily temperature change. After cracking the slabs, seating will be followed. Using pneumatic rollers may reduce the voids underneath the broken slabs, which will cause large vertical differential movement as well as pumping. In JRCP, the steel, if not cut, can prevent the PCC slabs from being properly seated. If large voids exist, the rehabilitation requires the use of sub sealing for those voids or placing a cushion layer (e.g., thick unbound layer) over the fractured slabs to reduce differential vertical deflections [4].

2.3.2.2. Rubblization for PCC

Rubblization treatment is defined as breaking the pavement into small pieces. The nominal maximum size is between 75 mm (3 in.) and 200 mm (8 in.). The rubblization process transforms the slab from poor cracked layer into a granular base layer for the HMA overlay. By rubblizing the existing PCC slabs, stress concentration developed at the crack tips will be eliminated, but the structural capacity may be decreased, thus a thick overlay can be a solution. Like the crack and seat method, the rubblization includes a roller compaction over the crushed concrete.

2.3.2.3. Mill and Inlay/Overlay for HMA

This method is used when the cracks are confined to the wearing surface or upper HMA layers. Milling and replacing can remove the existing cracks. For wide paving widths, the use of inlay is an economical solution. Increasing the thickness of inlay/overlay will be more effective to retard reflective cracking.

2.3.2.4. Hot-In-Place Recycling and Heat Scarification for HMA

The hot-in-place recycling and heat scarification method can eliminate existing cracks, especially surface-initiated cracks, prior to placing the HMA overlay. The heater scarification technique scarifies the existing pavement to a depth of about 19 mm (0.75 in.). The upper portion of cracks are removed and replaced with recycled materials and the lower portion of the crack is filled during the heating process. The recycling and remixing process provides an intact (uncracked) layer above the crack tips.

2.3.2.5. Full-Depth Reclamation for HMA

The full-depth reclamation (FDR) utilizes a cold-in-place recycling method. Existing HMA layers are pulverized so that all existing cracks are removed. Properties of FDR vary depending on the type of material being recycled and modifiers/additives. The modifiers/additives commonly used are emulsions, foamed asphalt, lime, fly-ash, and cement.

2.3.3. Stress/Strain Relieving Interlayer

The stress or strain relieving interlayer systems is used to dissipate energy by deforming (because of their flexibility). This interlayer is composed of two types: (1) stress-absorbing interlayer (an interlayer less than about 1 inches (25 mm) in thickness) and (2) a cushion layer (a layer greater than 3 inches (75 mm) in thickness). A cushion layer can be either open-graded HMA mixture or unbound granular layer.

2.3.3.1. Stress-Absorbing Interlayer

Stress-absorbing interlayer is a layer of soft material, and it is placed between the existing pavement and new overlay. The stress-absorbing interlayers can be deformed horizontally without breakage, thus dissipate the tensile stress, which mitigates thermally-induced reflective cracking. However, these interlayer systems do not reduce large vertical differential movements at joints or cracks in the underlying pavements. The stress-absorbing interlayer includes 1) chip seals, 2) Strata, 3) Interlayer Stress-absorbing Composite (ISAC), 4) Asphalt-Rubber Membrane Interlayer (ARMI), 5) polymer modified interlayer, and 6) fabrics (geotextiles).

Chip Seal:

A chip seal is a layer of asphalt binder covered by single-size chips (9.5 to 12.5 mm) which are compacted by a roller compactor. Although chip seals cannot prevent the horizontal movements of the underlying pavements, they can dissipate the stress caused by the movements. Chip seals can be categorized into three types based on the type of the binders:

- Conventional chip seals
- Polymer-Modified Emulsion (PME) chip seals
- Rubberized chip seals

The first two types are mostly used as a surface treatment. The rubberized chip seal is used to restore skid resistance on worn surfaces as a surface treatment method and also can be used to resist reflection cracking as an interlayer. Distresses such as cracking, flushing and base failures cannot be addressed with conventional or hot applied chip seals. Moreover it should be noted that deformation, rutting and shoving may not be addressed by chip seals of any kind [3, 8-10].

The main advantages associated with chip seal include:

- Cost effective treatments
- Good durability
- Ease of construction

Disadvantages of chip seal can be noted as:

- The thick binder layer and aggregate chips do not prevent or reduce the horizontal movements at cracks and joints, but dissipate those movements.

Strata (or Reflective Cracking Relief Interlayer):

The Strata, developed by SemMaterials, is another type of stress-absorbing interlayer. This system utilizes Styrene-Butadiene-Styrene (SBS) polymer instead of using rubber. This system consists of highly polymer-modified asphalt binder and fine aggregates. A high binder content makes the layer more flexible and enables the layer to dissipate tensile stress and strain under thermal expansions and contractions. This interlayer is normally 25 mm (1 in.) in thickness. Advantages and disadvantages of Strata are summarized as below [3, 10]:

<u>Advantages:</u>

- Protects the existing pavement structures from water damage.
- Provides a highly fatigue resistant material.

- Ease of mixing, placement, and compaction through the use of conventional HMA paving equipment.
- Saves in construction time and facilitating easy maintenance of pavement.
- Field results show that this system delays thermally induced and to some extent traffic induced reflective cracks much longer than the use of a typical HMA overlay.
- Recyclable

Disadvantages:

- There is little performance data to confirm the use of this system over longer periods of time.
- Proprietary product

Interlayer Stress-absorbing Composite (ISAC)

The ISAC is a composite layer that combines the benefits of a geotexile and stress-absorbing interlayer, and is designed to effectively alleviate or mitigate the problem of reflective cracks [11-13]. The ISAC system consists of a low stiffness geotextile as the bottom layer, a viscoelastic membrane layer as the core, and a very high stiffness geotextile for the surface layer. This system can relieve stress concentration at the crack tip and simultaneously provide reinforcement to the overlay [4]. Functions of the geotextile at the bottom of the ISAC can be listed as [11, 14]:

- Contain the rubber asphalt membrane.
- Fully bond with the existing pavement with the help of a tack coat.
- Accommodate large strain at the joint/crack to allow horizontal movement of the underlying pavement without breaking its bond with the slab

Asphalt-Rubber Membrane Interlayer (ARMI)

Asphalt rubber is made from mixing high concentrations of reclaimed rubber in hot asphalt. Several studies [15, 16] have shown that the ARMI seems to delay reflective cracking, but some tested sections show shoving and rutting problems. The ARMI has been commonly used as a reflective cracking mitigation method in the state of Florida.

2.3.3.2. Cushion Layer

A cushion layer can be defined as an interlayer that is greater than 3 inches (76 mm) in thickness. This layer absorbs or dissipates horizontal movements and differential vertical deflections developed at joints and cracks in the existing pavement. Cushion layers can consist of open-graded HMA mixture with large aggregate or an unbound aggregate/crushed stone base material. The open-graded HMA includes 25 to 30% air voids. Due to the thickness, this interlayer structurally enhances pavement structures, but it cannot be used sometimes due to elevation restriction. The thickness of the cushion layer is more than the stress-absorbing interlayer, thus it is suitable to absorb both vertical and horizontal movement. However, due to the large air voids, the cushion layer may have a potential of a forming a rutting as well as acting as a water conduit or reservoir between the overlay and the underlying pavement. Cushion layers are not recommended for flexible pavements. They are most appropriate on rigid pavements [3, 10].

2.3.4. Reinforcement of HMA Overlay

Reinforcements of HMA overlays are generally composed of steel and geosynthetics. These reinforcements placed at the bottom of HMA overlays are interlayer systems, but they are used to increase the tensile strength of the overlay and hold the cracks tightly together.

2.3.4.1. Steel Reinforcement

Steel reinforcement, one of the oldest interlayer systems used in HMA overlays, was used in many military airfield pavements during the 1950s and 1960s. Most study results have shown that the steel reinforcement performs better than control sections and other interlayer systems, but its use was gradually abandoned in the U.S. due to the difficulty in installing and recycling procedures.

2.3.4.2. Geosynthetics (Geotextile, Geogrids, Geocomposites)

Geosynthetics include geotextiles (fabrics), grids, and geocomposites. The mechanisms of the geosynthetic reinforcement are to relieve the stress/strain concentrations at joints and cracks. Geotextile and geocomposites can be used to reduce surface water infiltration to the lower layers.

- **Geotextile:** Geotextile (fabrics) can be either woven or nonwoven and are typically composed of thermoplastics such as polypropylene or polyester but also contain nylon, other polymers, natural organic materials, or fiberglass [17]. Common commercially available fabrics are Paveprep, Petropave, Petromat, Mirafi, Typar, and Roadglass.

- **Geogrid:** Geogrids may be woven from glass fibers or polymeric (polypropylene or polyester) filaments, or they may be cut or pressed from plastic sheets and then post tensioned to maximize strength and modulus. Reinforcing grids can enhance the tensile strength of an HMA overlay and its use can absorb horizontal tensile stresses and distribute them over a wider area.

- **Geocomposites:** Geocomposites are composed of fabric laminated onto a grid. They combine the advantages of both fabric and grid. The fabric improves the adhesion between the composite and a pavement surface while the grid increases strength and stiffness.

2.4. Case Studies Showing the Field Performance of Reflective Cracking Mitigation Methods

A variety of RC mitigation methods have been implemented in many states of U.S. and a wide range of results has been reported. The researchers have reviewed many case studies to collect the field performance of various reflective cracking mitigation methods. The summary of the literature review is described in this section.

Loria et al. investigated long-term performance of different techniques of treatments in Nevada [18]. They collected data by monitoring treated sections for fatigue, transverse and block cracking. Four techniques were used on 33 different locations, including cold in-place recycling (CIR), reinforced fabrics (RFs), stress relief courses (SRCs), and mill and overlay (MOL). For this study, the traffic condition of each location has been expressed as Annual Average Daily Traffic (AADT). The report contains more detailed information about the overlay design of each section. CIR projects with the lowest and highest AADT were among the best performers after 6 years while two CIR projects with medium AADT experienced fatigue cracking after 3 and 7 years in service. Three out of six RF projects did not experience any distress after 6 years in service while other three projects experienced reflective transverse cracking after 1 to 3 years. RF projects with high AADT were among the worst performers. Performance of three RF projects with low AADT was acceptable. The SRC project with high AADT was experiencing no distress after 8 years in service while reflective transverse cracking was evident in two SRC projects with medium AADT after 5 years. Although one MOL project performed well (without any distress) after 12 years, MOL projects were the only projects that experienced block cracking. Projects with this technique of mitigation with high AADT were among the worst performers in MOL projects. However MOL was effective in retarding the reflective cracking up to 3 years. The authors conducted statistical analyses based on their field measurements and concluded that the performance of the reflective cracking treatment is highly dependent on conditions of the pavement before construction of the treatment. In addition, they have ranked the techniques for Nevada’s condition as CIR, MOL, RF, and SRC [18].

The Mississippi Department of Transportation (MDOT) sponsored a study on the effectiveness of fabrics (geotextiles) in reducing the reflective cracking in HMA pavements [19]. This study included an extensive literature review on other state’s experiences and conducted a survey for the practices in Mississippi. From five districts in Mississippi, four of five districts had limited experience with fabrics. The survey results indicate that the overlay thicker than 2 inches total exhibited better effectiveness of the treatment. In addition, the application of fabrics is more effective in warmer climate regions. The drainage capacity of fabrics minimizes the damages due to freeze and thaw, and easy construction and low cost of the fabrics produce more benefit in the life-cycle-cost (LCC) analysis than the one without geotextile. The study indicates that fabric is ineffective at stopping thermal cracking but effective at mitigating RC in warmer regions. [19].

The Arizona Department of Transportation (ADOT) has conducted a study on the effectiveness of using a stress-absorbing interlayer, specifically Asphalt Rubber (AR), in retarding the reflective cracks on a very badly cracked concrete pavement [20]. They used a thin AR overlay

(2 inches) and monitored the pavement condition over nine years. Five factors that were monitored were percentage of cracking, International Roughness Index (IRI), rut depth, skid resistance, and maintenance cost. Before overlaying, concrete pavement was treated by a crack-and-seat method that makes PCC slabs to small pieces with 0.5-m spacing. A 3-in HMA overlay was placed and a 2-in AR overlay was placed on the HMA that included a finer gap-graded mix. The results of field monitoring over nine years illustrated that all five condition parameters have been improved. The cost of the AR is about twice more expensive than conventional HMAs but the AR overlay requires less routine maintenance with better performance.

A team from the Texas Transportation Institute (TTI) studied geosynthetics as a reflective cracking mitigation method [21]. They used fabrics, grids and composites to reduce the severity or delay the appearance of reflective cracking. Three different locations were selected considering cool, moderate and mild climate zones. The location with moderate climate included an AC overlay over JCPs (Waco) while two other locations were AC overlays over flexible pavements (Amarillo and Phar). AADT, annual rainfall and average daily temperature range data were available for each location. All test sections were monitored for transverse and longitudinal reflective cracking for about five to six years. Due to thick milling depth in Phar District, a small percentage of reflective cracking was observed after six years. In Waco, the mitigation methods performed better than control sections. However, after 3.5 years of the placement of overlay, the rate of reflected cracks increased. Only Pave-Prep exhibited a reasonable delay in appearance of reflective cracking. In Amarillo District, most treatment methods exhibited worse field performance compared to the control section. This section experienced the highest traffic load and maximum average daily temperature range compared to the other sections. The common observation through all test locations was that the rate of reflection cracking apparently increased after three to four years of the overlay placement. It can be explained that aging of asphalt mixture can accelerate the damage on the overlay mixture.

In another study conducted in Texas [22], the Rolling Dynamic Deflectometer (RDD) and Overlay Tester (OT) were used to evaluate the effectiveness of a Rich Bottom Layer (RBL) and SMA in retarding reflective cracks in jointed concrete pavements (JCPs). In the section of SH-12 in the Beaumont District, after a full-depth milling of the overlay, the JCP was overlaid with 1-in. RBL, 2 inches of AC, and 1.5 inches of porous friction course. This section has shown no visible cracks after 2 years of service. The author concluded that the main reasons for this good performance on SH-12 are the flexible RBL mix and the thick overlay. The OT test indicates that the RBL involved a life exceeding 900 cycles. In the section of US 96 in Beaumont District, 3-inches of SMA was placed over a Continuously Reinforced Concrete Pavement (CRCP). A SMA showing the OT life exceeding 700 cycles was placed over the CRCP. After 5 years later, the visual survey exhibited no significant cracks.

A study was conducted in Illinois [23] to evaluate the effect of interlayer systems in mitigation of reflective cracking in PCC pavements. Sand mix interlayers, Sand Anti-Fracture (SAF) interlayers, and Interlayer Stress-Absorbing Composites (ISAC) were used in this project. Ground Penetration Radar (GPR) was used before and after each treatment to locate joints, patches, dowel bars and other discontinuities in the existing pavement. In addition, a cracking-map survey was conducted to identify the locations of reflective cracks. The sand mix interlayer section consisted of a 19-mm sand size aggregate mixture and 8% PG 76-28 fiber modified asphalt binder, topped with 38 mm dense graded HMA. The ISAC sections were treated with 90 cm width ISAC layers on transverse joints topped with 57 mm leveling and wearing HMA course. The SAF interlayer, similar to the sand mix, was placed with 19 mm thickness topped with a wearing HMA course. Reflective cracking appearance ratio was defined as total number of reflected cracks to the total number of joints, patches, and existing cracks. In this parameter, the ISAC section lasted more than other sections when both severity and quantity of reflective cracks were taken into account. The results show that the ISAC provided relatively better performance than other interlayers after 6 years of crack monitoring and the sand mix interlayer retarded reflective cracks compared to control sections over a 2-yr monitoring period.

In another study an intensive literature review was done to find the effect of nonwoven pavement fabrics on retarding the reflective cracking in PCC and HMA pavements [24]. Detailed results of the literature review are presented in Appendix A. Four different treatments were compared as follow:

- Paving fabric with a chip seal over unpaved roads and subgrades (Case1)
- Paving fabric and chip seal over existing asphalt-cement concrete (ACC) pavements (Case 2)
- Paving fabric and ACC overlay over existing Portland cement concrete (PCC) pavements (Case 3)
- Paving fabric and ACC overlay over existing ACC pavements (Case 4)

In Case 1, all the literatures indicated a successful experience in applying fabrics and chip seal during monitoring periods of the pavements. Case 2 was not successful at all the locations, probably due to higher traffic load comparing to case 1. Literature review results for case 3 shows that using fabrics on PCC pavements can retard the development of reflective cracking; however, paving fabric is not entirely effective in combating the reflection of existing transverse cracks or joints when there is existing excessive vertical movement or high deflection. Thirty sites were evaluated in case 4. Twenty six of them found that using fabrics effectively resulted in retarding reflective cracks while other four sites reported that insufficient overlay thickness resulted in early crack observation. Based on different case studies in this study, overlay thickness should be carefully designed to get the most effect of the paving fabrics. In a study in Georgia, 60% of reflective cracking was observed after 3 years in a pavement with a 2 inch overlay while less than 20% of reflective cracking was observed after 6 years with a 4 inch overlay.

A study conducted in Illinois in 2004 compared the effect of utilizing a Strata (or called as RCRI) in five different states (i.e., Illinois, New Jersey, Virginia, Missouri and Kansas). In all cases the thickness of the Strata was 1 inch covered with 3 to 4 inches of HMA overlay. Control sections were conventional HMA overlay with the thickness of 4 to 5 inches. In all sections Strata sections outperformed the control sections[25]. A further study on control sections were done to investigate the effect of site condition on reflective cracking of HMA overlays. By plotting traffic condition, overlay thickness, structural strength of existing pavement, PG type of asphalt binder and minimum flexural stiffness of Strata layer versus average crack propagation per year, it was concluded that traffic load and overlay thickness have insignificant relationship with the RC propagation. Furthermore, it was indicated that a successful Strata treatment may require a minimum life of 100,000 cycles in overlay tester.

The Nevada DOT's Materials Division performed an extensive investigation to identify promising RC mitigation techniques [26]. A component of this study was a literature review of performance expectations of RC mitigation methods. Table 2.1 displays the results of projects outside of Nevada with different RC mitigation methods. The literature review covered six RC mitigation methods, cold in-place recycling (CIR), glassgrid, fabric interlayer, asphalt rubber interlayer with an overlay (about 1.5"), stress-absorbing membrane interlayer (SAMI), and crumb rubber overlay.

Hajj et al (2008) [26] also reviewed NDOT projects that used the different RC mitigation techniques. The results of this review can be seen in Table 2.2. The NDOT used a 0.375-in. or 0.75-in. OGFC on top of the following pavement projects. These mitigation techniques were CIR, reinforced fabric, stress relief course, and mill and overlay. The results on the table also show the traffic levels for the associated projects and the observed field performance. This study also reviewed the results of long-term field performance of pavement projects by Washoe County, Nevada (Hajj et al 2008). The Washoe County projects used an asphalt overlay along with nonwoven geotextile fabrics, Petro mat, or no fabric. The summary of results can be seen in Table 2.3. The use of fabrics retarded RC for longer than overlays without fabrics in this study.

Haltz et al. (1998) [27] indicated that the second largest application of geotextiles in North America is for mitigating reflective cracking. The performance of the paving fabrics is significantly impacted by the condition of the old pavement surface and the installation practices. With the favorable conditions, reflective cracks can be delayed for approximately 2 to 5 years compared to an overlay without a paving geotextile layer. Using fabrics in overlays also affects the quality of drainage in the overlay, as the fabric will function as a moisture barrier. Barksdale, R.D. (1991) concluded that the cost of 0.5 to 0.6 inch of asphalt concrete is almost equivalent to the cost of a full-width paving fabric [28]. The California Department of Transportation concluded that a fabric interlayer will delay reflective cracking the same as 1.2 inches of HMA overlay. Buttlar, et al. (1999) studied the cost effectiveness of using a non-woven, polypropylene paving fabric in the State of Illinois [29]. These fabrics were placed either in strips longitudinally over lane-widening joints or over the whole area of pavement. The life spans were increased from 1.1 to 3.6 years.

In 1993, the University of Illinois completed a laboratory study to evaluate ISAC. The results indicated that the ISAC layer was highly effective in retarding reflective cracking while covered by 2.5 in. AC overlay in compare with control section[13]. Subsequently, they implemented the ISAC in the field. ISAC could retard formation of reflective cracking 1 to 3 years compared with the control section [30].

Louisiana State University conducted a study to evaluate the performance of chip seal as a RC mitigation method. It was found that chip seal was the most promising result in terms of performance and economic worthiness. In some test sections, chip seal could retard reflective cracking 4 times longer than the control section [31]. Based on the literature review by the Nevada DOT, asphalt-rubber chip seal overlaid with 1.5-in. conventional dense-graded HMA or gap-graded HMA delayed reflective cracking up to 5 years [21].

A Strata study conducted in Missouri indicates that Strata placed on an AC pavement could retard formation of reflective cracking about 2 years. In another study in Iowa, Strata was placed on JCPs and retarded reflective cracking for the first 2 years. At the end of the fourth year, the reflective cracking percent on control section was 29% while the treated section was 17%. As a general conclusion, Strata can additionally delay reflective cracking about 2 years [32].

The effect of increased overlay thickness was studied by several investigators [7, 33]. In a Texas study, overlays with 1.25, 1.5, 2, 2.4 and 2.5 inches were considered. The performance was evaluated by measuring the percent of reflection cracking over time. Overlays up to 2 inch in thickness had shown relatively similar performance while the 2.4- and 2.5-in. overlays showed significantly improved performance in retarding reflective cracking. It was found that 2.5-in. overlays showed the delay of reflective cracking about 2 to 3 years than the 2-in. overlays [7, 33].

Table 2.1: Summary of literature review performed by Hajj et al [26].

Treatment	Description	Performance
Cold in-place recycling	Remove and mill the upper layers of the existing pavement with specialized recycling equipment then mix with virgin materials to produce a strong flexible base course.	Promising performance for roads with up to 13,000 ADT and 200,000 annual equivalent single axle loads.
Glassgrid	Geosynthetic material consisting of connected parallel sets of intersecting ribs with openings of sufficient size.	Benefits in retarding or preventing reflective cracking are not clear. Field performance has varied from excellent to very poor. Concerns when used on rough surfaces.
Fabric interlayer	Geosynthetic comprised solely of textiles. A paving fabric interlayer provides the generally acknowledged functions of a stress-absorbing interlayer and a waterproofing membrane. The stress-related performance has been easily verified by the observed reductions of cracking in pavement overlays.	Effective when used for load-related fatigue distress. It did not performed well when used to delay or retard thermal cracking. Optimum performance highly associated with proper construction procedures. The key factor is proper tack-coat installation. In general, overlays reinforced with fabrics have shown better performance than unreinforced overlays under same conditions.
Asphalt rubber interlayer + thin overlay (about 1.5")	Asphalt rubber chip seal overlaid with conventional dense graded HMA or gap graded HMA.	Reduce and/or delay reflective cracking for a period of 5 years.
Stress absorbing membrane interlayer	A thin layer placed between an underlying pavement and an HMA overlay for the purpose of dissipating movements and stresses at a crack in the underlying pavement before they create stresses in the overlay. SAMIs consist of a spray application of rubber or polymer-modified asphalt as the stress-relieving material, followed by placing and seating aggregate chips.	Successful in reducing the rate of reflective cracking.
Crumb rubber overlay	Produced by adding ground tire rubber to HMA using the wet process.	Ranged from successful to devastating failures depending on percent of crumb rubber in mix.

Table 2.2: Summary of NDOT reflective cracking mitigation techniques review [26]

Treatment	Description	Application Conditions		Performance
		Traffic	Pre-rehabilitation Pavement Condition	
Cold in-place recycling (CIR)	CIR of minimum top 2.0" of existing HMA materials and overlaying it with a minimum of 2.5" dense graded HMA mixture.	Up to 14,000 AADT.	No severe alligator cracking.	Stopped reflective cracking for 5 years after construction
Reinforced fabric (RF)	Cold milling 2.0" of existing HMA layer, placing fiberglass yarns, and overlaying with 2.0" Type II (1 inch maximum size) dense graded HMA.	Between 1,000 and 10,000 AADT.	No severe alligator cracking.	Retarded reflective cracking for at least 3 years after construction and reduced the rate of reflected transverse cracks 5 years after construction.
Stress relief course (SRC)	Cold milling 2.0" of existing HMA layer, placing a 1" stress relief course and overlaying with 2.0" Type II (1" max size) dense graded HMA.	Up to 40,000 AADT.	NA	Stopped reflective cracking for 3 years after construction. Rate of reflected transverse cracks accelerated 5 years after construction.
Mill and overlay (MOL)	Cold milling 1.0" of existing HMA pavement and overlaying it by 1.0" HMA mixture manufactured with an AC-10 asphalt binder.	Up to 40,000 AADT.	NA	Reflected fatigue and transverse cracks 1 to 2 years after construction.
	Cold milling 1.0" of existing HMA pavement and overlaying it by 1.0" HMA mixture manufactured with an AC-20P asphalt binder.	Up to 4,000 AADT.	NA	Stopped reflective cracking for 3 years after construction. Minor reflected transverse cracks 5 years after construction.
	Cold milling 1.5" of existing HMA pavement and overlaying it by 1.5" HMA mixture manufactured with an AC-20P asphalt binder. (*)	Up to 2,000 AADT.	NA	Stopped reflective cracking for 3 years after construction. Minor reflected transverse cracks 5 years after construction. (*)

Table 2.3: Summary of Washoe County, Nevada RC mitigation techniques review [26]

Treatment	Description	Performance
NF-1.5	No Fabric + 1.5" HMA overlay	Retarded reflective cracking for 1 to 3 years after construction.
NF-2.0	No Fabric + 2.0" HMA overlay	Retarded reflective cracking for 1 to 3 years after construction.
NF-2.5	No Fabric + 2.5" HMA overlay	Retarded reflective cracking for 1 to 5 years after construction.
F-2.0	Non-woven Geotextile Fabric + 2.0" HMA overlay	Retarded reflective cracking for 1 to 5 years after construction.
F-2.0s	Non-woven Geotextile Fabric + 2.0" HMA overlay + slurry seal some years prior treatment application	Retarded reflective cracking for 3 to 5 years after construction with some sections showing reflective cracking within the first year after construction.
P-2.0	Petromat + 2.0" HMA overlay	Retarded reflective cracking for 1 to 5 years after construction. Most of the sections exhibited reflective cracking, either fatigue or longitudinal and transverse cracking at the end of the 5 year analysis period.
P-2.0s	Petromat + 2.0" HMA overlay + slurry seal some years prior treatment application	Retarded reflective cracking for 1 to 5 years after construction on half of the sections and for at least 5 years on the remaining half of the sections. The sections did not develop fatigue cracking during the 5 year analysis period.

2.5. Parameters Affecting Reflective Cracking

There are several specific factors that influence the performance of reflective cracking mitigation methods. These factors include 1) overlay thickness, 2) existing pavement condition, 3) base/subgrade support condition, 4) environmental factor, and 5) traffic level.

2.5.1. Overlay Thickness

A study in Texas [24] demonstrated the effect of overlay thickness and a combination of thicker overlay and paving fabric with respect to reflective cracking. The effect of the paving fabric with different overlay thicknesses was investigated and the results are shown in Figure 2.2. As seen in the figure, three thickness of AC overlay were studied with and without fabric. Increasing the overlay thickness significantly retards the RC. The 152.4-mm overlay exhibited less than 20% RC while the 50.8-mm overlay shows 100% RC after 5 years.

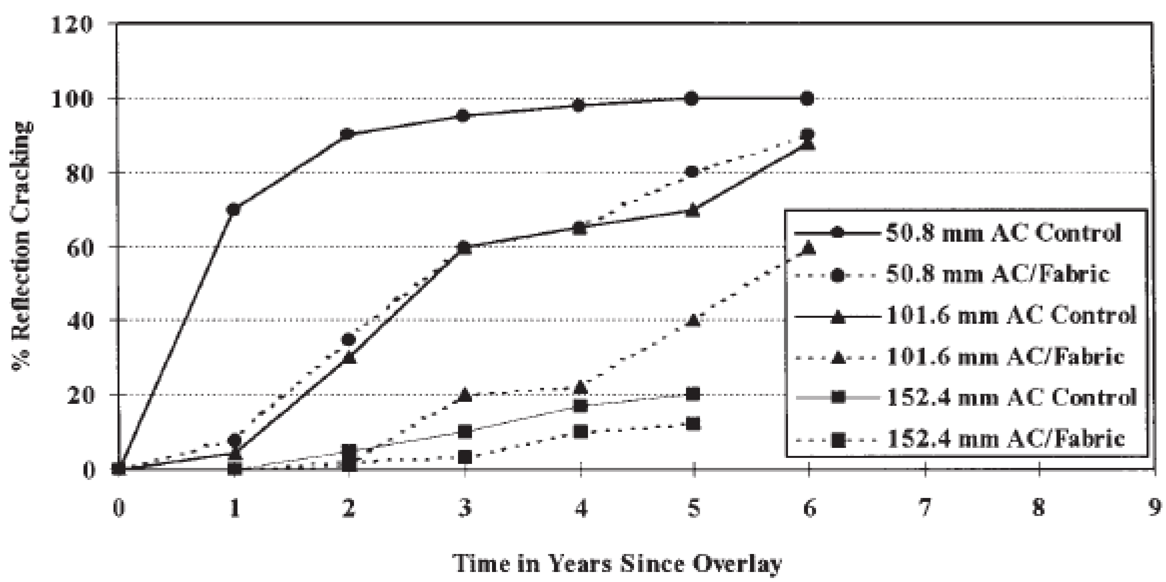


Figure 2.2: Reflective cracking over time for sections having different overlay thickness [24]

2.5.2. Existing Pavement Condition

The extent and severity of cracking as well as other distresses present in the existing pavement should be examined and quantified to select an appropriate rehabilitation scheme. Existing surface cracks need to be repaired by either filling or sealing before the placement of the overlay. Pre-overlay treatments are necessary to remove existing cracks that will lead to premature reflective cracking. In particular, an interlayer such as fabric requires surface treatment prior to the overlay. In some situations with minimal width of cracks, sealing may not be necessary as the fabric can be expected to bridge over these thin cracks, but larger width cracks (greater than 6.4 mm (0.25 in.)) would require the repair of existing cracks.

2.5.3. Base/Subgrade Support Condition

Base and subgrade support conditions also significantly affect long-term performance of the overlay. Weaker base and subgrade supports create larger deformation and higher stress/strain concentration at the tip of crack, resulting in faster development and propagation of reflective cracking. In order to assess the base and subgrade conditions, either visual inspection or deflection testing can be used. Deflection tests such as FWD can provide more accurate structural information such as the modulus of pavement layers; however other functional conditions such as drainage may not be identified by the FWD test. Thus, the combination of visual survey and deflection measurements would be recommended. Ground penetrating radar (GPR) can also provide additional information such as moisture content, subsurface anomalies, and thickness of each layer.

2.5.4. Environmental Conditions

The most important environmental effect to be considered is temperature. In severe cold climates, freezing and thawing of pavements cause volume changes (e.g., expansion due to water freezing) as well as softening subgrade soils during thawing. Daily temperature change causes the contraction and expansion of pavements and also curling (upward and downward) of PCC slabs. These environmental effects cause damage to pavements and accelerate reflective cracking. Pavement performance associated with reflective cracking varies geographically, especially between warm and cold climate regions. Figure 2.3 shows the typical time until reflective cracking is observed in the HMA overlay.

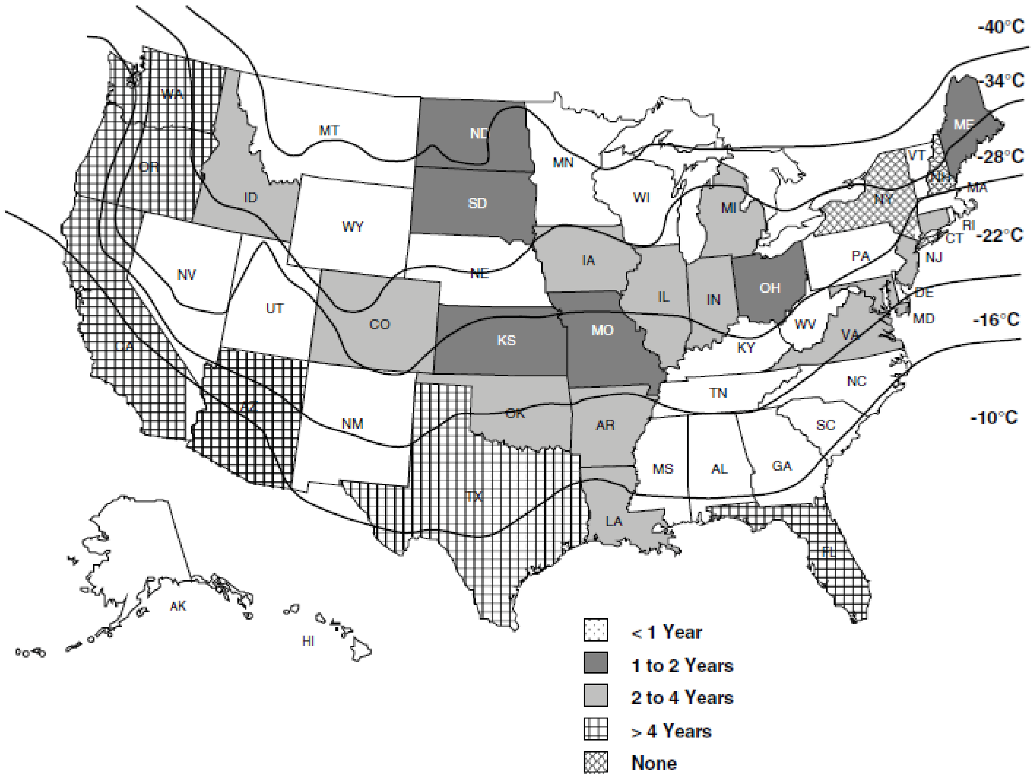


Figure 2.3: Time to observe reflective cracking after placing the HMA overlay [34]

2.5.5. Traffic Level

Bennert and Maher [34] conducted a survey on state highway agencies asking typical traffic levels (ESALs) where reflective cracking on composite pavements (HMA overlay over PCC) has been problematic. The ranges of ESALs asked in the survey were (1) < 3 million, (2) 3 to 30 million, and (3) > 30 million. Most agencies responded to 3-30 million ESALs (58%), 39% responded to greater than 30 million, and the remaining 3% responded to less than 3 million ESALs. The results show that reflective cracking was observed on composite pavements having 3 to 30 million ESALs and higher but not less than 3 million ESALs [34]. It is important note that not many PCC pavements are constructed for low traffic-volume roads (e.g., farm-to-market roads).

2.6. Cost-Benefit Studies on RC Mitigation Methods

Reflective cracking mitigation methods associated with performance, constructability and cost effectiveness of each method has been studied [17]. The in-place cost of reflective cracking mitigation methods is related to specific product used, quantity to be placed, local experience with its installation, labor costs and the general condition of the market place [17].

2.6.1. PCC Pavements

Timm et al. [35] have compared different mitigation methods in the state of Alabama. For PCCs, the mitigation methods can be divided into two categories: Stress absorbing interlayer and fractured slab approaches. They studied three different rehabilitation methods in the second category that are crack and seat, break and seat, and rubblization. The study mainly focused on the rubblization method. In the field projects, old PCC pavements were rubblized and then HMA overlays were placed. In order to explore the effectiveness of these methods, data were obtained from nine rubblized sections in the state of Alabama, which has been rehabilitated over eleven years. The average cost of rubblization process was about $1.99 per square yard and the costs of remaining construction works such as HMA overlay should be taken into account for the whole rehabilitation cost [35].

For the fractured slab approaches the Nevada DOT evaluated the costs of PCC pavement rehabilitation methods in 1999 and the results were as follows [36]:

- Cost of Break/Crack and Seat : $341,000/mile
- Cost of rubblization : $561,000/mile
- Cost of total reconstruction : $2 million/mile

Also, the initial cost of the break/crack and seat method is said to be less than the initial cost of the rubblization method. However, the life cycle cost of both methods would be same after a 35 year period of analysis because the rubblization performs better than the break and seat.

2.6.2. HMA Pavements

Fabrics have been used widely for the purpose of reflective cracks mitigation. The second largest application of geotextile products in North America is in the area of mitigating the reflective cracking [27]. These geosynthetics are being used in the AC overlays over either HMA or PCC. The surface condition of the existing pavement and installation has significant impact on the performance of the paving fabrics. With the favorable conditions, reflective cracks can be delayed for approximately 2 to 5 years, compared to the overlay without the fabric. Using fabrics also affects the quality of drainage in the overlay, as it will function as a moisture barrier. This will eventually increase the pavement structural capacity and will lead to a longer pavement life or a thinner design for the AC overlay.

In the city of Philadelphia, the performance of geotextiles and sealing was studied over a 10-year period [37]. The performance data was gathered over 8 years and both fabric and sealing treatments retarded reflective cracking compared to control sections. Regarding cost effectiveness of these mitigation methods, the cost of using fabrics was $1.79 to $2.39 per square meter, and cost of sealing was reported to be $0.95 per square meter. A cost analysis concluded that using fabrics as a rehabilitation technique is not a cost-effective treatment strategy.

Barksdale concluded that the cost of 0.5- to 0.6-inch asphalt concrete is almost equivalent to the cost of a full-width paving fabric [28]. The California Department of Transportation (Caltrans) reported that fabric delays reflective cracking at the same rate as 1.2 inches of HMA overlay does and the fabric would cost 50% less compared to1.2 inches of HMA [27].

In the state of Illinois, the cost effectiveness of using a non-woven, polypropylene paving fabric as a RC mitigation technique was studied [29]. These fabrics were placed either in strips longitudinally over lane-widening joints or over the whole area of pavement. The result showed that this method will retard the longitudinal cracks, but not the transverse cracks. More specifically, the strips increased the life span by 1.1 years, but treating the whole area increased it 3.6 years. LCCA showed that these methods are marginally cost effective. According to the LCCA result, medium size projects (between 1 to 6 miles of two-lane road) resulted in 4.5% reduction in cost while small projects (less than 1 mile of two-lane road) produce almost the same cost as conventional HMA. In large projects (longer than 6 miles of two-lane road), 6.2% saving in cost has been reported [29].

Another study in the state of Illinois evaluated the retarding ability of reflective cracking by using several interlayer systems [38]. They studied five different interlayer systems: area- and strip-type nonwoven fabric; two strip-type composite; and a fine, high polymer content HMA interlayer system. A LCCA tool was used in order to evaluate the cost-benefit of those interlayer systems. This LCCA was able to develop a decision-making procedure for the decision makers to choose different systems that satisfy their requirements [38].

Tighe et al. [39] also studied the LCCA of mitigating reflective cracking, and mainly focused on the economic asset of reducing the reflective cracking. Reducing reflective cracking has several economic benefits regarding:

- Longer service life of pavements;
- Lower maintenance costs;
- Decreased vehicle operation costs; and
- Decreased user-delay costs.

The results indicated that a reduction in transverse crack spacing from 5 to 20 m resulted in an extension of service life by 5 years and also will save the maintenance costs by the amount of $ 25000 (2002 U.S. dollars) per two-lane kilometer [39].

The Arizona Department of Transportation has studied the use of asphalt rubber (AR) to mitigate reflection cracking [20]. In 1990, a project section was constructed on a highly trafficked Interstate 40. The aim of this project was to determine whether the AR can reduce reflective cracking. It was reported that the AR application could save approximately $18 million in cost. The maintenance cost per mile for the studied section is shown in Table 2.4. The maintenance cost dropped dramatically after 1990. In Figure 2.4, the maintenance cost with and without using of AR has been compared. Over a 10 year period, the pavements without the AR have shown approximately 3 times higher cost of maintenance compared with the pavements with the AR.

Table 2.4: The maintenance cost per mile [20]

	Percent Cracking	Ride IRI inch/mile	Rut Depth inches	Skid Mu Meter Number	Maintenance Dollars Per Mile	Traffic 18 Kip ESAL's per year
PCCP 1989	9	132	NA	41	6227	1,500,000
After Overlay						
1990	0	42	0.50	69	0	1,600,000
1991	0	42	0.12	64	146	1,700,000
1992	0	48	0.14	69	121	1,800,000
1993	0	56	0.13	60	173	1,900,000
1994	0	44	0.12	66	274	2,000,000
1995	0	51	0.11		248	2,100,000
1996	0	53	0.11		623	2,300,000
1997	0	49	0.10	58	575	2,400,000
1998	0	53	0.11	65	872	2,500,000

1 in. = 25 mm. 1 mi = 1.6 km. 1 kip = 4.45 kN.

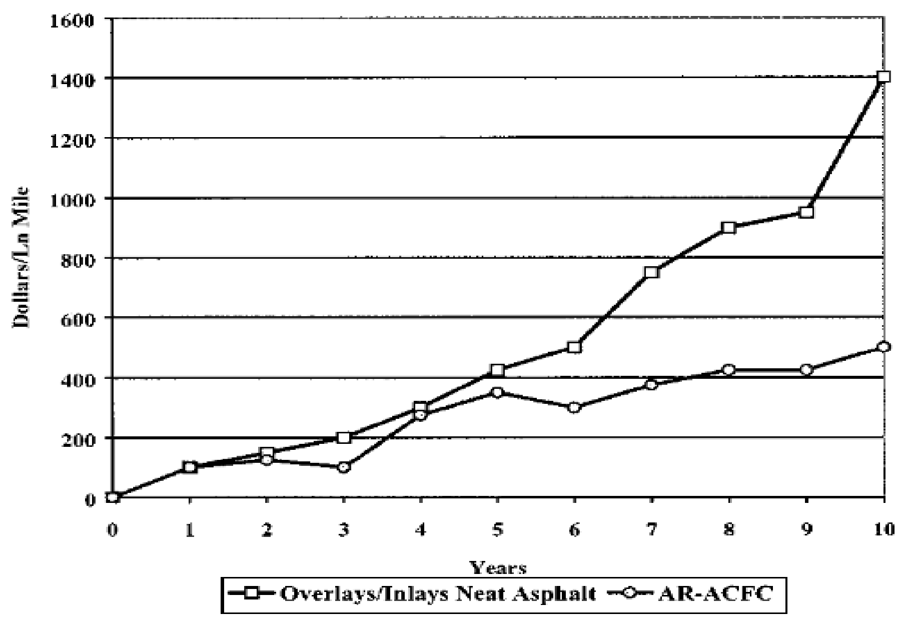


Figure 2.4: The maintenance cost with and without using of AR [20]

2.7. Nationwide Survey

A survey was issued to all the SHAs to obtain information on SHAs' current practices for reflective cracking mitigation measures. Focus of the survey was placed on the AC overlays over flexible pavements. The researchers created a web link for the survey, and the link was distributed to all state DOTs in U.S. through the FDOT system. The survey was developed with following agenda:

(1) typical overlay thickness without the mitigation technique and its field performance (i.e., how long it delays reflective cracking);

(2) typical field/laboratory methods in pavement evaluation program;

(3) most effective reflective cracking mitigation methods and their selection criteria;

(4) pre-overlay treatments for flexible pavements;

(5) HMA overlay design methods or minimum HMA thickness; and

(6) experiences with reflective cracking mitigation techniques.

Surveys were sent out to all 50 SHAs electronically and 18 of the 50 SHAs responded. The survey results were analyzed and a summary of those six topics are presented below.

2.7.1. HMA Materials

This is not a part of the survey in this study but the researchers did not include this particular question because Bennert and Maher [34] already conducted a survey across the U.S. regarding the typical overlay material (e.g., binder grade and aggregate size). Thus, their findings on this specific question are presented herein.

For better understanding of the current practice, the findings are presented herein. According to his survey results, for aggregate in the overlay mixture, a majority of the states use either a 9.5-mm Superpave mix over a 12.5-mm Superpave mix or 12.5-mm Superpave mix over a 19-mm Superpave mix. The correlation between asphalt binder and the onset of reflection cracking was reviewed (see Table 2.5). The states observing the longest delay of reflective cracking are Texas and Florida, whose low-temperature performance grade (PG) is between -16 °C and -10 °C, and their binder used is PG 76-22. Despite the use of stiffer binders, Texas and Florida reported reflective cracking was delayed for more than 4 years, which is longer than other states that utilize equal or less stiff binders. Under similar environmental condition, stiffer binders have lower cracking resistance; thus, they are more susceptible to reflective cracking. The survey results shown in Table 2.5 explain that seasonal temperatures may be the dominant factor to control the field performance of AC overlays with respect to reflective cracking; warmer regions produce longer service life from a reflective cracking viewpoint.

Table 2.5: Performance grade of asphalt binder and reflective cracking life of different states

State	LTPPBind	Binder Used	Reflective Cracking
North Dakota	-34 °C/ -40 °C	64-34 over 58-28	1 to 2 yr
South Dakota	-34 °C	64-34 or 64-28	1 to 2 yr
Kansas	-22 °C/ -28 °C	70-22	1 to 2 yr
Arkansas	-16 °C/ -22 °C	76-22	2 to 4 yr
New Jersey	-22 °C	76-22	2 to 4 yr
Ohio	-28 °C	70-22 over 64-28	2 to 4 yr
Florida	-10 °C	76-22	> 4 yr
Texas	-10 °C / -16 °C	76-22	> 4 yr

2.7.2. Most Effective Reflective Cracking Mitigation Treatments

SHAs were asked about the best performing RC mitigation methods on their experience. Based on the findings of the literature review, the choices included in the questionnaire were screened down to the final six methods: (1) paving fabrics; (2) reinforced HMA overlay (i.e., geogrid); (3) stress-absorbing membrane interlayer (SAMI); (4) Strata; (5) crack-arresting layer (i.e., unbound aggregate layer); and (6) increased overlay thickness. Another question was what the decision factors were for determining the design of reflective cracking mitigation strategy. As seen in Figure 2.2, seven SHAs choose trial-and-error; four SHAs chose cost, and three SHAs chose research. One SHA (Alaska) chose the rapid construction time as the most important decision factor. SHAs were also asked to provide information as to whether or not the mitigation technique previously used was successful. For this study, the definition of a successful reflective cracking mitigation technique is one that provided a minimum of 5 years of service before reflective cracking was observed. Figure 2.3 shows the overall satisfactory level for those six selected mitigation treatments. The result shows that the combination of interlayer systems (SAMI, Strata, and crack-arresting layers) and increased overlay thickness would be the most successful strategy.

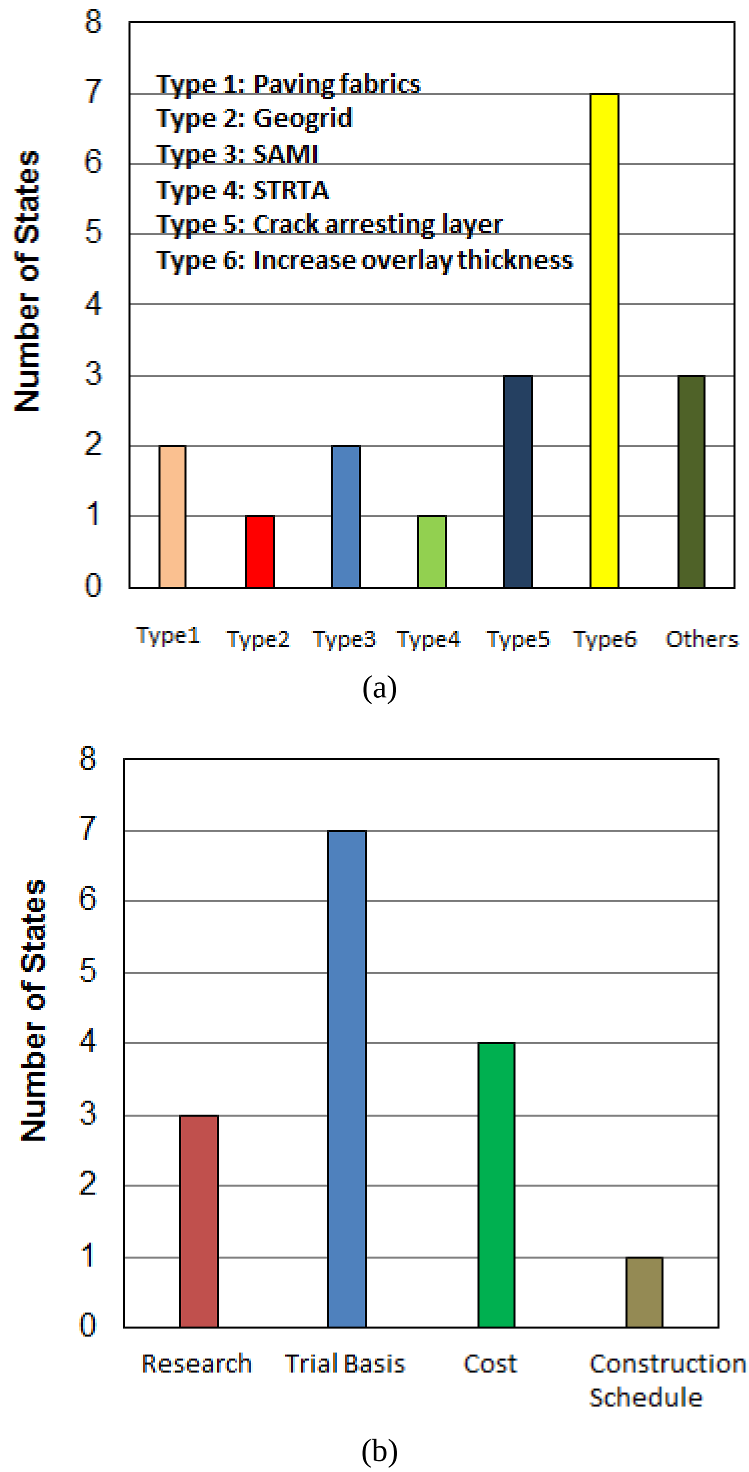
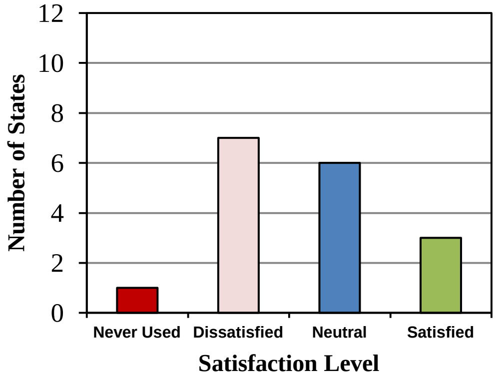
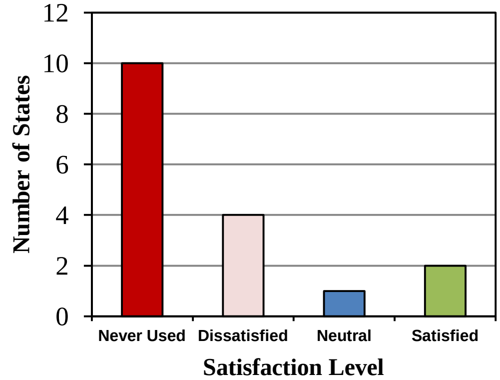


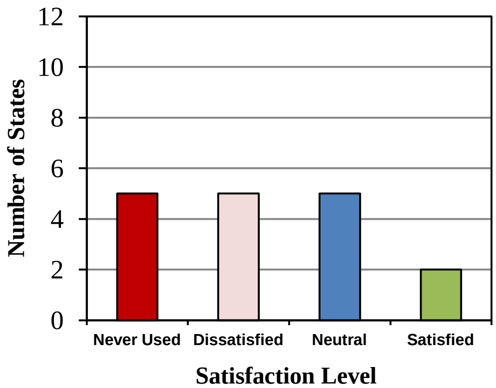
Figure 2.5: Survey results: (a) the most effective method for RC mitigation and (b) selection criteria of RC mitigation method.



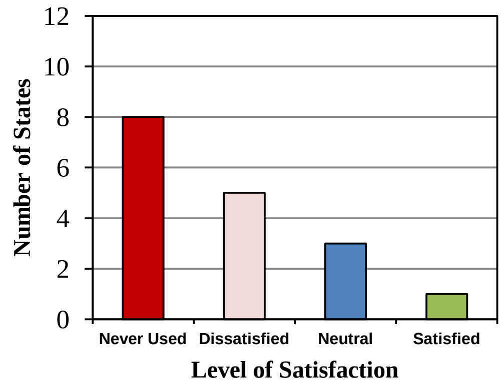
(a) Paving fabrics



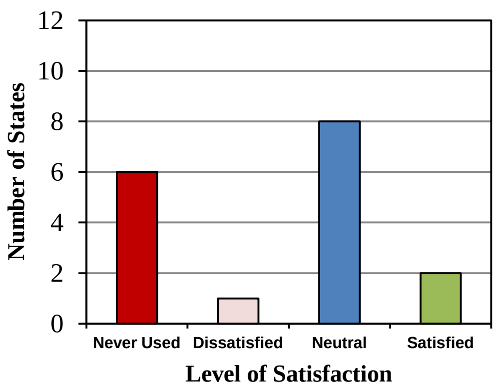
(b) Geogrid Reinforcement



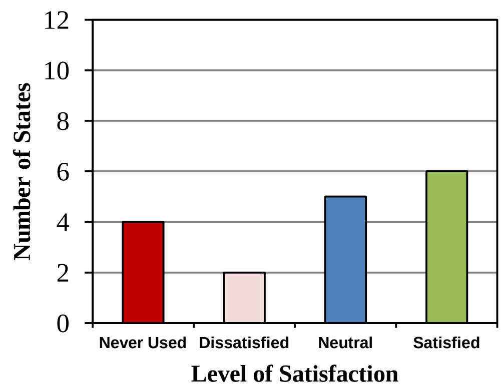
(c) SAMI



(d) STRATA



(e) Crack arresting layer



(f) Increase overlay thickness

Figure 2.6: RC method of treatment and satisfaction level

2.7.3. Forensic Investigation Methods for the Reflective Cracking Mitigation Selection

The use of field forensic testing methods provides in-situ information on pavement structural condition, geotechnical, and environmental conditions so that engineers understand the major causes of pavement deterioration and properly design the new overlay system. The SHAs were asked to provide information on the use of Falling Weight Deflectometer (FWD), Ground Penetrating Radar (GPR), Dynamic Cone Penetrometer (DCP), coring and sampling, visual distress survey, traffic counts and vehicle classification, and laboratory testing. Distribution of different field forensic testing methods is shown in Figure 2.4.

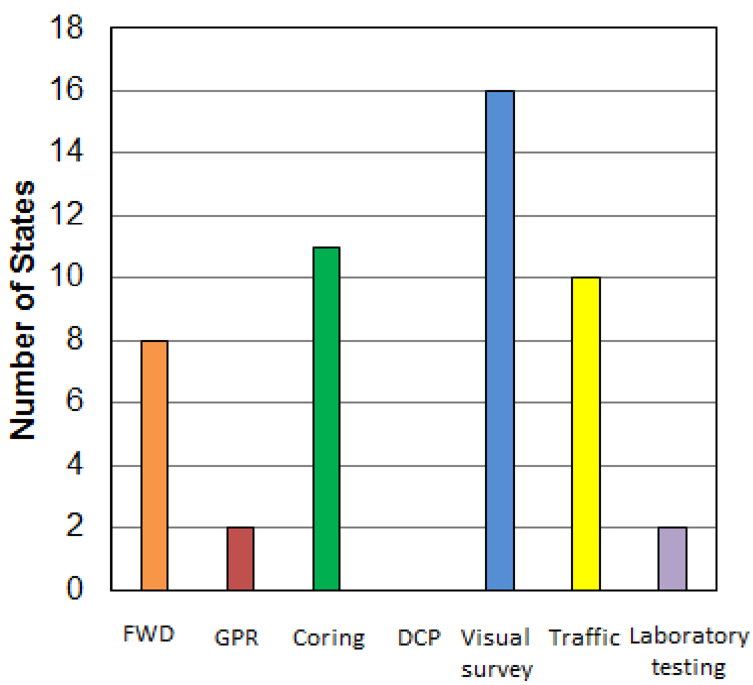


Figure 2.7: Survey results: forensic investigation method on the existing pavement.

2.7.4. Pre-Overlay Treatments on the Existing Pavements

Proper pre-overlay treatments can improve the structural capacity of the existing pavements and will retard reflective cracking in the overlay. SHAs were asked to provide typical pre-overlay treatments they have utilized for the existing flexible pavements. Figure 2.5 and 2.6 summarizes typical pre-overlay treatments for the exiting flexible and rigid pavements, respectively. The data seen in Figure 2.6 was surveyed by New Jersey DOT [34]. The most common HMA treatment has been to mill and overlay, with hot-in place recycling being the least used treatment. On the other hand, the most common PCC treatment has been to replace poor joints and slabs, with void filling being the least used treatment.

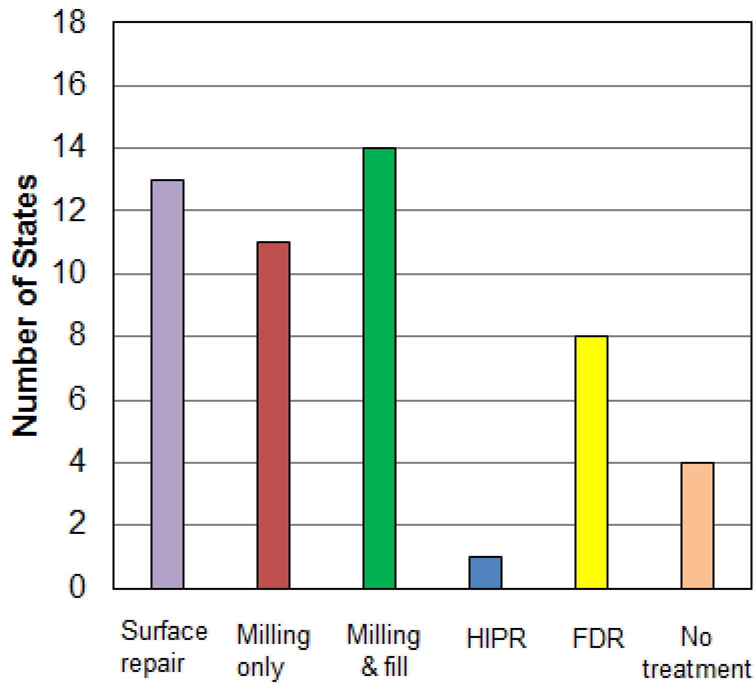


Figure 2.8: Typical treatments on the existing pavements prior to the overlay

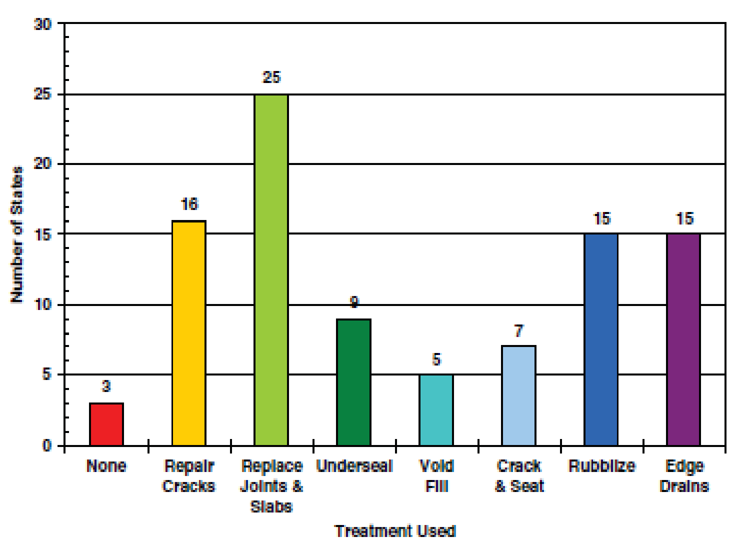


Figure 2.9: Survey results: common PCC treatments [34]

2.7.5. Field Performance of the Selected Mitigation Method

SHAs were asked to provide details on the performance expectation of the overlay to be placed. The survey asked two questions regarding (1) the performance expectation for the overlay without any mitigation method and (2) the performance expectation of the selected mitigation method. It was found that the majority of SHAs do not have a current standard to rate the performance for RC mitigation methods. 'Performance goal' is defined as the expected life of RC mitigation methods in the unit of years until RCs are observed. The performance goal can be established on case studies showing specific time to observe the RC. Table 3 summarizes the performance goal of each SHA.

Table 2.6: Survey results on the performance goal with typical overlay and selected RC mitigation method.

State	Typical Overlay Thickness (in.)	Performance Expectation in service life (years)	The Most Successful RC Mitigation Technique	Performance Expectation of the Selected RC Mitigation Method
Illinois	2-4	1-2	Increased Overlay Thickness	1 year or 2 and also minimize the severity.
Alaska	2-3	1-2	Paving fabrics/geotextiles	4-5 years
Idaho	0.15-0.2	2-4	HMA overlay reinforcement (i.e., geogrids, steel, fiberglass)	4 to 6 year improvement
Iowa	4 in. in 2 lifts	2-4	Strata	N/A
West Virginia	1.5	1-2	Increased Overlay Thickness	1 in./year crack propagation
Washington	<6	> 4	Increased Overlay Thickness	About extra 2 years (note: WSDOT does not have a major problem with reflective cracking)
Missouri	3.75	2-4	Increased Overlay Thickness	N/A
Utah	1.5-3	1-2	Other- CIR Interlayer	N/A
Ohio	1-3.5	2-4	Paving fabrics/geotextiles	We have seen fewer cracks and less severe cracks after ~5 years of performance.
Indiana	1.5	1-2	Increased Overlay Thickness	Increase overlay may delay +/- 1 year per inch of thickness.
Arkansas	2-6	N/A	None	3 years
Minnesota	1.5-3	1-2	SAMI	2 years (estimate)
Nevada	2	> 4	Crack-Arresting layer	Results vary depending on climate, traffic levels, and quality of construction and severity of distresses. Typically, cracks are mitigated or reduced for 5-15 years.
Georgia	1.5	2-4	Crack-Arresting layer	An additional 2 to 4 years
Wyoming	2	2-4	Increased Overlay Thickness	More than 5 years.
Massachusetts	1.75	2-4	Other-Milling, SAMI + Thicker Overlay	5 years of additional life.
Montana	0.15-0.2	1-2	Crack-Arresting layer	N/A

2.8. Summary

In this chapter, a comprehensive literature study was conducted across the country in the areas of (1) RC mechanisms, (2) existing and practical RC mitigation methods, (3) RC affecting parameters, (4) case studies showing field performance of various RC mitigation methods, (5) cost-benefit studies on RC mitigation methods, and (6) survey to all SHAs in the US.

Findings from the literature reviews associated with the AC overlays over HMAs and JCPs are summarized below.

Asphalt pavements:

- Various RC mitigation methods have been used by each SHA but mixed results have been reported. To properly evaluate the performance of RC mitigation methods, the performance should be assessed compared with control sections where similar traffic, road materials, climate, and site conditions exist.

- Most previous studies have reported the same RC mechanisms for the overlay over HMA and the overlay over JCP. Not many studies have differentiated the performance of RC mitigation methods for the overlay over HMA versus the overlay over JCP.

- Many researchers believe that thermal-induced movement is the main cause of initiating RC at the bottom of an AC overlay and traffic loading accelerates the deterioration, particularly cracking propagation through the overlay [40].

- Aging of asphalt mixture can accelerate the damage on the overlay mixture. RC appears around 3 to 4 years after the overlay placement no matter what mitigation techniques were used. It is believed that aging of the overlay mixture causes stiffer materials.

Concrete pavements:

- Compared with the overlay over HMAs, the overlay over PCCs generally involves much larger vertical differential movements at joints/cracks as well as slab curling due to temperature differentials. In addition, slab expansion and contraction will occur, but horizontal movements may be lower than those of asphalt pavement due to lower CTE values. In particular, vehicle loading under upward slab curling during early morning can produce significant vertical movements (also tensile stress at the crack tips) at joints, resulting in RCs within a short period of time.

- Several studies [15, 41] have shown that reflection cracks of HMA overlays over PCC slabs may initiate from the surface even when no traffic loading was applied. This explains the mechanism shown in Figure 2.1 due to the slab curling of the underlying PCC slabs.

- Literature has shown that geosynthetic applications to rigid pavements are not effective in retarding the RC. On the other hand, several studies have shown that stress-absorbing interlayers or cushion layers are more effective in retarding the RC. The survey issued to all SHAs by Bennert and Maher presents the same trend that the SAMI and RCRI have shown successful filed performance [34].

In addition, a nationwide survey to all SHAs was conducted to learn current practices of RC mitigation management. On the basis of the study, the following conclusions were drawn:

- A majority of SHAs do not have a overlay design method that specifically considers RC mitigation.

- Most SHAs select their best performing (or currently using) RC mitigation method based on their experience and trial.

- Visual surveys are the most widely forensic investigation tool used for evaluating the existing condition prior to the new overlay. In addition, FWD, Coring, and traffic characterization are considered in pavement evaluation program.

- Among reflective cracking mitigation methods, increase of overlay thickness (40 % of the respondents) is the most preferred method and a crack-arresting layer (18 % of the respondents) (i.e., unbound aggregate layer) is the second most popular. Several interlayer systems are being used such as paving fabric, geogrid, chip seal, ARMI, ISAC, Strata (proprietary product), and crack-arresting layer (i.e., unbound aggregate layer).

- Pre-overlay treatments being used in SHAs are surface repair, milling and fill, milling only, hot-in place recycling, and full-depth reclamation. The two most common methods are milling only and milling and fill prior to the overlay.

- The survey results shown in Table 3.1 explain that temperature over the year may be the most dominant factor to control the field performance of the AC overlay; warmer regions produce longer service lives from a reflective cracking viewpoint.

Over the last two decades, there have been extensive studies in mitigating RC over the nation.

However, the performance of each method varies from site to site and also from time to time. It is obvious that there is no one solution identified as the top RC mitigation technique. As discussed, there are many parameters affecting the field performance of RC such as climate, traffic, and material type (binder, aggregate, etc.). Thus, regional conditions would be critical inputs in selecting an optimum RC mitigation strategy. In Chapter 3, Florida's climate and RC mitigation practice will be presented.

3. CURRENT PRACTICES OF REFLECTIVE CRACKING MANAGEMENT

3.1. Introduction

Chapter 2 presents a summary of literature study and nationwide survey. In this chapter, the current practice of RC mitigation management in the state of Florida was investigated. For understanding of the FDOT practice, the researchers have reviewed the published FDOT reports and also conducted personal interviews with pavement engineers. In Florida, an ARMI has been mainly used as a reflective cracking mitigation method but mixed field performance of an ARMI has been reported. Florida's road and climate conditions as well as rehabilitation practice are discussed.

3.2. FDOT Practice

In order to identify best performing reflective cracking mitigation methods, understanding the FDOT's current practices regarding pavement rehabilitation as well as reflection cracking mitigation management is necessary. FDOT's research reports and publications have been reviewed. In addition, the researchers have had many discussions with many pavement engineers through phone conversations as well as surveys. The key issues to be investigated are as below:

1) How has reflective cracking been managed in Florida,
2) How has the FDOT evaluated the surface distress,
3) What are Florida's conditions,
4) What mitigation treatments have been tried and studied, and
5) What lessons have been learned from the previous studies (especially ARMI projects).

A summary of findings associated with Florida's conditions are presented below.

- The majority of Florida's state maintained roads are surfaced with asphalt pavement (approximately 98 % or more). Therefore, the research focus was placed on the RC mitigation method in AC overlays over HMAs.

- Stiffer asphalt binder (either PG 67-22 or 76-22) is being used in Florida. Although summer in Florida creates high pavement temperature, rutting is not a critical problem due to those stiff binders and well established mixture designs. Surface-initiated cracking, which is top-down cracking, is the main pavement distress observed in Florida.

- The majority of cracking in the state of Florida is top-down rather than bottom-up cracking. The mechanism of top-down cracking can be explained by thermal effects (temperature gradients, thermal stress), loading effects (tension induced by truck tire ribs), and aging effects (binder hardening). Top-down cracking is commonly developed in the form of longitudinal cracking along wheel paths.

- During milling, there is a possibility that deep top-down or full-depth cracks may not be entirely removed. Thus, depending on the crack condition (e.g., top-down, bottom-up, and full-depth) in the underlying HMA, different stress concentrations and distributions may be developed at the bottom of the new overlay. For example, top-down cracking in the underlying layer may cause less stress concentration at the tip of crack compared to the cases with full-depth and bottom-up cracks. Details of stress and strain analyses under varied crack conditions will be presented in Chapter 4.

- An ARMI is most commonly used when cracks cannot be entirely removed during milling. A recent accelerated pavement testing (APT) experiment showed that rutting may be increased when an ARMI is used close to the surface because of greater shear stress. Rut profiles showed that much more asphalt material moved laterally and created larger humps on the outside of the rutted wheel path (indicating instability or greater shearing of the mixture). Considering the stress concentration and distribution with the ARMI, a proper depth that can sufficiently reduce the magnitude of vertical stress onto the ARMI layer will be necessary.

- Annual precipitation in Florida is higher than many other states. Moisture, along with aging, may also affect reflective cracking development in the asphalt overlay [42-44].

- A visual survey easily identifies reflection cracking in the AC overlay over JCPs because most reflective cracks appear at transverse and longitudinal joints (due to large vertical differential movements). On the other hand, reflection cracking in the AC overlay over HMAs is difficult to detect unless a crack map is carried out before and after the overlay placement. Performance data that include crack mapping before and after are not available; thus data analyses with field performance data collected in Florida was unavailable.

3.3. ARMI Studies in Florida

3.3.1. A Review of FDOT's ARMI Projects

An ARMI has been used as a common method to mitigate reflective cracking in the state of Florida. The FDOT has conducted several research projects to evaluate the performance of an ARMI in mitigating reflective cracking. The summary of laboratory and full-scale accelerated pavement testing (APT) studies is presented below.

Heavy Vehicle Simulator (HVS) Testing Study (Report No.: FL/DOT/SMO-12-552):

Accelerated pavement testing (APT) conducted with the Heavy Vehicle Simulator (HVS) was conducted to evaluate the performance of an ARMI. A summary of findings is presented below.

- This HVS study found that an ARMI contributed to instability rutting under slow moving loads and typical summer pavement temperature.

- The ARMI also resulted in higher rutting compared to the overlay without an ARMI.

- Transverse rut profiles indicated that all sections with an ARMI exhibited greater shear flow and mixture instability than sections without an ARMI.

- A 2-inch overlay with and without an ARMI was constructed on PCC slabs. Within 2 weeks, 50% of the joints with an ARMI were observed to have reflection cracks prior to any HVS loading. Cores showed shallow cracks that appeared to originate from the surface.

Laboratory CSIC Test (Report No.: BDK75 977-60 Report):

- This study was conducted to evaluate the effectiveness of an ARMI in mitigating reflective cracking. Repeated load fracture tests (Composite System Interface Cracking (CSIC) test) were conducted on specimens taken from the APT lanes after the HVS test. The specimens were cored samples with and without the ARMI. Numbers of cycles to failure and damage rate were obtained from the CSIC tests. Testing results show that specimens without an ARMI outperformed the specimens with an ARMI in terms of reflective cracking resistance.

State Road 2, Baker County (Report FIN No.: FDOT 27020-3509):

In January 1998, the FDOT initiated a study in Baker County to evaluate the long-term performance of an ARMI on five unique test sections on the eastbound lane of State Road 2. Results for deflection, ride quality rutting and cracking were obtained. Of the five test sections, test sections 1 and 2 incorporated the use of an ARMI where test sections 3, 4, and 5 did not. From the 2011 results, section 1 had the largest rut depth of about 0.24 inches as well as the most cracking at about 225 SF/1000 SF of cracking. Section 1 also showed a substantially larger amount of transverse cracking over the other four sections at about 27 SF/1000 SF or transverse cracking.

State Road 10, Gadsden County (Report FIN No.: FDOT 411695-1-5201):

The original roadway of State Road 10 was constructed in the late 1920's as a 7-inch PCC pavement with unpaved shoulders. After several rehabilitation efforts the roadway was expanded from 2 lanes to 4 and reflective cracking has been observed in the two inside lanes. The purpose of this study is to explore the effectiveness of alternate methods to counter reflective cracks from occurring. The field study included five, 1,368-feet test sections and located within the two eastbound and the two westbound traffic lanes.

The design called for milling 3 inches of existing asphalt and putting back 1.5 inches of Superpave (SP) 12.5-mm structural course in Sections 1, 2, 4 and 5, and 2.5 inches of the same in Section 3 (control section). In addition, Section 1 received a 0.5 inch asphalt overbuild; Section 4 received 1.0 inch of an Open-Graded Crack Relief (OGCR) layer; Section 5 received a 0.5 inch ARMI. All test sections received a 1 inch of Friction Course (FC) 9.5. The performance is evaluated based on deflection, cracking, rutting, and ride quality. As of 2011 results were obtained, and with respect to the observations of cracks, Sections 5 and 3 in the west bound traffic lane show the highest amount of cracks equaling 26.59 and 13.29 $ft^2/1000\ ft^2$ of cracks, respectively. No cracks were observed in either of the eastbound lanes.

State Road 60, Hillsborough County (Report No.: FHWA-DP-37-14):

This project investigated ten 1,000-ft sections. Four sections included an ARMI, two received an asphalt rubber seal coat, and the remaining four involved standard construction with varied thickness (no ARMI). The ARMI layer was placed directly below an Open Graded Friction Course (OGFC) in two of the sections while the other two sections with an ARMI included a 1.5 or 2.5-in. overlay, and leveling course above the existing pavement in the other two sections. After six months, extensive rutting and bleeding was observed in the wheel paths of the sections with an ARMI placed below the OGFC. No significant rutting or surface distresses were found in the sections with the ARMI placed below the structural and leveling courses during the six month evaluation.

I-10 Rehabilitation (Report No.: FL/DOT/SMO/05-482):

This project evaluated the effectiveness of long-term field performance of an ARMI when used with the crack-and-seat rehabilitation method. A Total of 14 two-lane sections (all located on the I-10 corridor in North Florida) were monitored from the time of reconstruction and periodically thereafter. The performance data showed that the crack-and-seat method with a stress relief membrane (an ARMI layer) could be an effective reflective cracking mitigation strategy for PCC pavements.

3.3.2. Survey to FDOT Districts

In addition to the review on FDOT reports, the survey was issued to the selected FDOT Districts to understand the field performance of ARMI across the state of Florida. The responses have been received from pavement design engineer, District (Districts 1, 3, and 7) and Turnpike engineers. Inputs from those field engineers were valuable information that can be used to determine the performance goal of ARMI. Comments from each pavement engineer are summarized as below.

- The Turnpike has used An ARMI in Lake, Osceola, Polk, Palm Beach and Hillsborough Counties. These pavements have shown no major reflective cracking and no extensive rutting after 5 years. Pre-ARMI pavements on the Turnpike in Lake County had reflection cracking as early as 2 years and cycles of 5 to 9 years before reaching a 6.5 crack rating. Pavements after milling deeper and adding an ARMI have lasted anywhere from 8 to 13+ years. Performance data shows, on average, the sections with ARMI are lasting 2 to 5 years longer than those without.

- In Districts 1 and 7, the pavements with an ARMI have exhibited good performance. In addition, coring was performed for all projects where an ARMI was placed. No major reflective cracks have been observed but rather top down cracking, and most were at a typical design life of around 15 to 20 years.

- District 3 has unique bases including Sand Clay, SBRM and SAHM which are prone to severe block cracking. An ARMI has been included on many projects since 1994 with mixed field performance. While coring these projects now for resurfacing, it was noticed that the reflective crack hits the ARMI and then traverses to another point and extends upward with less severity. Some engineers feel that an ARMI provides very little protection from reflective cracking and that it contributes to rutting. However, most agree that an ARMI has proven to be beneficial in delaying cracking for several sections on I-10 where the existing concrete was cracked and reseated (aggressively). The project included an ARMI, 5” Type SP Structural (Traffic Level D) with ¾” OGFC.

3.4. Summary and Conclusions

In this chapter, the current practices of reflective cracking mitigation management in the state of Florida and in the U.S. were investigated. A literature review, personal interviews, statewide and nationwide surveys were conducted with an emphasis of the AC overlay over flexible pavements. Regarding Florida’s conditions and FDOT’s current practices, a summary and conclusions are presented below.

- An ARMI has been FDOT’s primary reflective cracking mitigation method. . The ARMI has shown mixed field performance in terms of mitigating reflective cracking across the state of Florida. Rutting has been observed in some Districts but clear cause was not identified. It seems that most Districts are satisfied with an ARMI performance when used in PCC.

- Florida's climate conditions include warmer and higher precipitation than many other states. Exposure to weathering (e.g. sunlight, rainfall, etc.) likely accelerates aging of asphalt pavement. In addition, the road system in Florida is composed of approximately 98% asphalt pavement and top-down cracking is a major distress type. The research focus should be on reflective cracking in the AC overlay over HMAs not the AC overlay over PCC slabs.

- Based on the extensive literature review, most studies have focused on AC overlays over concrete pavements. Depending on the type of underlying pavement, the deformation behavior and stress/strain development around the crack tip will be different. For instance, PCC slabs create vertical differential movements at joints while HMA creates bending-shape deformation. In addition, temperature loading may cause slab curling of PCC slabs while horizontal movements in HMAs is a major response. Clear mechanisms should be theoretically studied.

- Other Florida conditions involve the use of stiff asphalt binder (e.g., PG 67-22 or PG 76-22), faster asphalt aging, and top-down cracking. With severe top-down or full-depth cracks in the existing pavements, if the milling depth is not sufficiently deep, milling may not be able to remove all cracks and some portions of top-down or full-depth cracks will remain. The new AC overlay will be placed on top of remaining cracks; thus, different cracking mechanism will be developed depending on cracking conditions in the underlying layer.

4. NUMERICAL ANALYSIS

4.1. Introduction

Depending on whether the underlying pavement is PCC or HMA, the deformation mechanism of the AC overlay to be placed will be different. That is, material properties (elastic vs. viscoelastic), modulus, and crack/joint shape and size in the underlying pavement will control the strain and stress developed at the bottom of the overlay. Over the last two decades, extensive studies have been carried out regarding the mechanism and mitigation of reflective cracking for AC overlays of jointed concrete pavements (JCPs); however, not many studies with a focus on AC overlays of HMA have been reported. Unlike asphalt pavement, the underlying JCPs will create significant vertical differential movements at joints under wheel loads. On the other hand, the underlying asphalt pavement will be deformed with convex–shape bending under wheel loads. Depending on the crack type (e.g., full-depth crack, top-down, and bottom-up cracks), the stress and strain concentration at the tip of crack will be different.

In this chapter, numerical simulations using finite element model (FEM) method have been conducted to clearly understand the mechanism of reflective cracking in AC overlays of flexible pavements. The FEM analyses were aimed at:

(1) evaluation of the behavior of crack with different crack conditions (full-depth crack, partial top-down crack, and partial bottom-up crack in the underlying HMA),

(2) effect of varied loading positions,

(3) effect of different reflective cracking mitigation methods, and

(4) effect of the thickness of mill and inlay.

The reflective cracking mitigation methods evaluated in the FEM simulations were increased thickness of mill and inlay and two interlayer systems that are paving fabric (geotextile) and an ARMI. The commercial software ANSYS was used for the FE simulations.

4.2. Fracture Modes of Reflective Cracking

A general mechanism of reflective cracking from the structure viewpoint has been well studied and documented (see Chapter 2). Reflective cracking through the AC overlay is due to repeated vertical or horizontal movements at the joint/crack of underlying pavement under traffic and temperature loading. However, those mechanisms are more suitable for the overlay over PCC slabs. Reflective cracking mechanism in the AC overlay over HMAs can be re-interpreted from the fracture mechanic viewpoint. Multiple fracture modes are seen in Figure 4.1. These modes are based on the fracture characteristics of materials. Mode I better represent the major fracture modes for the overlay over asphalt pavements while Mode II represents those of the overlay over PCC slabs.

- Mode I is referred to as an opening mode and is caused by loads applied normal to the crack plane. Cracks can be opened and closed due to horizontal movements. This mode might be described with horizontal stress or strain in the X direction.

- Mode II is referred as sliding mode and caused by in-plane shear loading, which leads to the faces of crack sliding against each other. The sliding mode is in the Y direction in Figure 4.1. Vertical differential movements at cracks of existing asphalt pavements under traffic loading can cause this sliding mode. This mode may be described with XY-direction shear stress or strain.

- Mode III is referred as tearing mode and caused by out-of-plane shear loading, which causes sliding of the faces of crack parallel to the crack leading edge. Although this mode may occur if the crack plane is not normal to the direction of traffic, this mode of loading is neglected in this study for simplicity.

Mostly, reflective cracking observed in the field includes the combination of all three modes. Principal stress or/and principal strain is the combination of horizontal and shear stress or/and strain. Strain is directly related to pavement deformation; thus, principal strain could represent the critical crack behavior. In this FEM study, principal stress and strain were used to predict the behavior of cracks and locations of crack initiation and propagation.

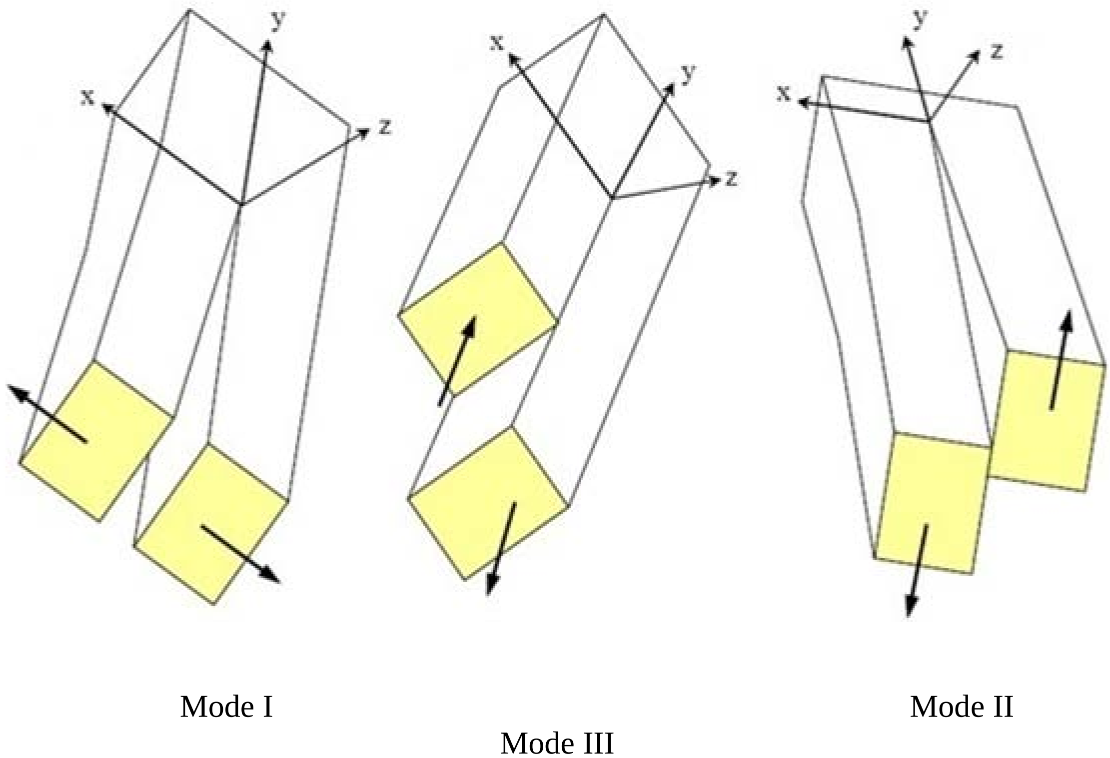


Figure 4.1: Fracture Modes of Materials [45]

4.3. Descriptions of Finite Element Modeling

4.3.1. Cracking Conditions Considered in the FEM Study

After milling, existing flexible pavements can have different cracking conditions: (1) full-depth crack, (2) partial bottom-up crack, and (3) partial top-down crack. The states of Florida, New Jersey, Pennsylvania, Indiana, and Texas have reported top-down cracking as a major pavement distresses. Internationally, the UK, Netherlands and Japan have also reported top-down cracking issues [41, 46]. In Florida, approximately 85% of the deficient pavements are due to cracking not rutting [47]. More than 90% of cracking are in the form of top-down [48, 49]. The mechanism of top-down cracking in Florida may be due to stiff asphalt binder (PG 76-22 or PG 67-22), lime stone base (relatively strong), aging effect (binder hardening) and weathering.

Milling is a typical treatment on the existing deteriorated pavements prior to the placement of new AC overlay. If severe top-down cracks (e.g., significantly deep) or full-depth cracks, standard milling may not be able to remove all the existing cracks, and partial top-down or full-depth cracks will remain. Placing a new AC overlay will involve those cracks in the underlying pavement layer. Figure 4.2 shows cored samples having different crack conditions in the state of Florida.

(a) (b) (c)

Figure 4.2: Crack patterns: (a) Partial top-down cracking; (b) Partial bottom-down cracking; and (c) Full depth cracking [50]

4.3.2. Modeling Description

This chapter describes the FE modeling of pavement structure. A commercial FE analysis package [51] was used for the computational simulations. Models could be created using command-prompt-line input or the Graphical User Interface (GUI). For the model in this study, the command-prompt-line input was used to create the model.

4.3.2.1. Geometry and Boundary Conditions

A layered linear elastic analysis was conducted with 2D PLANE STRESS elements. The PLANE183 element which is 2D-plane stress element in ANSYS requires linear isotropic material properties to model each layer. This FE mesh consisted of 112,820 eight-node quadrilateral elements. To investigate stress/strain concentration at the top and bottom of the three different crack types in the underlying layer, small cracks were inserted in the existing pavement for each case. To model the boundary conditions, nodes on both vertical edges must be constrained in the transverse direction. The nodes on the bottom edge were constrained in the X and Y directions and displacement set equal to 0 (See Figure 4.3).

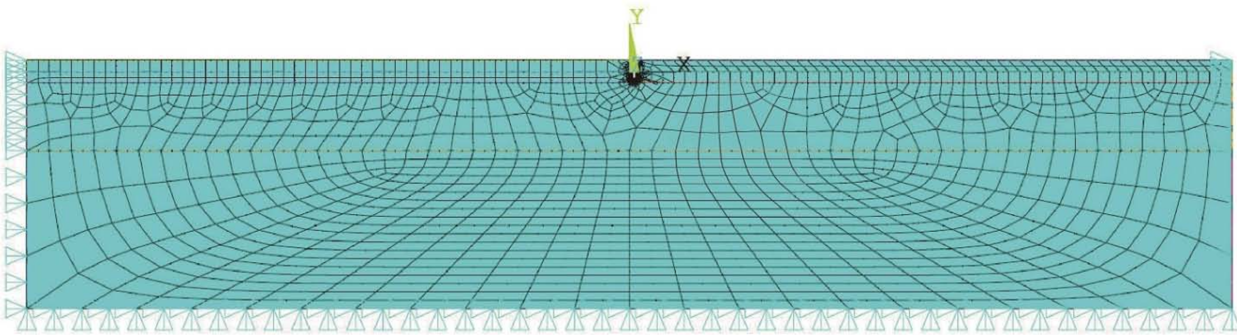


Figure 4.3: FE models showing mesh and boundary conditions

4.3.2.2. Properties of Material

Parameters for the material modeling are defined Table 4.1 and Table 4.2. The modulus for each layer was based on other numerical and experimental studies [50, 52-55]. Koh (2009) evaluated resilient modulus, creep compliance, and strength tests by using the Superpave IDT test at the following temperatures: 14°F, 32°F, 41°F and 50°F (-10°C, 0°C, 5°C and 10°C). The Strategic Highway Research Program [54] conducted resilient modulus tests and flexural stiffness tests with four different temperatures: 32°F, 68°F, 104°F, and 140°F (0°C, 20°C, 40°C, and 60°C).

To consider temperature changes in different season, two temperatures of 50 °F and 68 °F were chosen; 50 °F (10 °C) for the average low temperature and 68°F (20 °C) for the average high temperature in Florida. The properties of HMA in Table 4.1 show the resilient modulus at temperature of 68°F (20°C). Table 4.2 shows the resilient modulus of HMA at temperature of 50 °F (10 °C). An AC overlay with variable thicknesses is applied to the cracked existing HMA.

In the developed FE models, the modulus of elasticity for the ARMI and fabric were assumed to be 1004.7 ksi and 1.1 ksi, and the total thicknesses of the ARMI and fabric interlayer were 0.5 in. and 0.25 in., respectively. All materials were considered linear elastic with the respective moduli shown in Table 4.2 for the different investigated cases.

Table 4.1: Material properties and geometry at temperature of 68°F (20°C) [53, 54, 56, 57]

Layers	Depth (in.)	Elastic Modulus (ksi)	Poisson ratio(ν)	Unit Weight (lb/ft^3)
HMA Overlay	2	500.4	0.3	145.1
Existing HMA	6	580.1	0.3	145.1
Base	8	56.6	0.33	148.3
Subbase	12	24.7	0.35	149.6
Subgrade	120	10.2	0.4	114.6

Table 4.2: Reflective cracking mitigation types at temperature of 50°F (10°C) [45, 52-55, 58, 59]

	Overlay only			Overlay with ARMI			Overlay with Fabric		
Material	Depth (in.)	Modulus (ksi)	Poisson's ratio	Depth (in.)	Modulus (ksi)	Poisson's ratio	Depth (in.)	Modulus (ksi)	Poisson ' s ratio
OGFC	0.75	1,015	0.35	0.75	1,015	0.35	0.75	1,015	0.35
HMA Overlay	3	1,573.2	0.3	2.5	1,573.2	0.3	2.75	1,573.2	0.3
ARMI	-	-	-	0.5	1004.8	0.35	-	-	-
Fabric	-	-	-	-	-	-	0.25	1.1	0.43
Existing HMA	6	1,738.5	0.3	6	1,738.5	0.3	6	1,738.5	0.3
Base	8	239.2	0.35	8	239.2	0.35	8	239.2	0.35
Subbase	12	16	0.4	12	16	0.4	12	16	0.4
Subgrade	120	10.1	0.45	120	10.1	0.45	120	10.1	0.45

4.4. Results of FE Analyses

4.4.1. Effect of Different Crack Conditions

Cracking in the existing pavement includes full depth cracks, partial top-down cracks, and partial bottom-up cracks. These three crack types have been observed in the field as seen in Figure 4.2. Figure 4.4, shows graphical presentations of the pavement structures having different crack types. The three cases seen in Figure 4.4 were numerically simulated in the FE study. To compare the influences of different crack conditions on the overlay behavior, three different cracks were inserted into the existing pavement. The full-depth crack is 0.15 in. in width and 6 in. in height while the top-down and bottom-up cracks are 1-in. deep (see Figure 4.5). A static load was applied on the top of the HMA overlay along the same line of crack which is in the existing pavement. A pressure of 116 psi (800 kPa) was used for the static load. To evaluate the pattern of crack initiation associated with strain concentration, two locations on the crack (Node no. 1 and 2 for the full-depth crack, Node no. 3 and 4 for the partial top-down crack, and Node no. 5 and 6 for the partial bottom-up crack as shown in Figure 4.5) were selected for the measurement of stress and strain. Materials properties and geometries shown in Table 4.1 were used as input values.

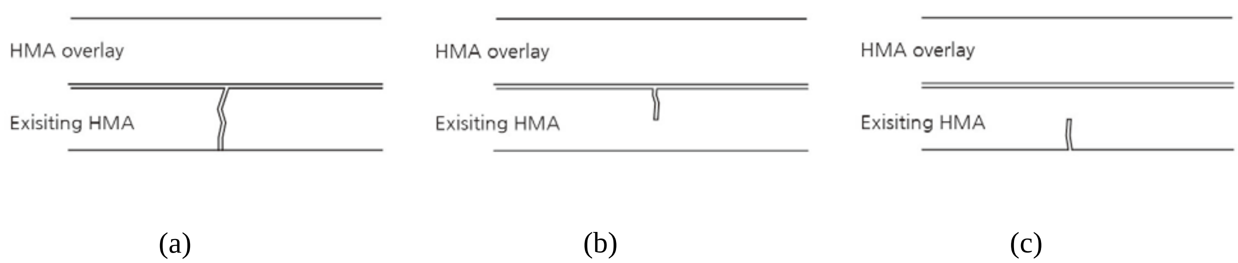


Figure 4.4: FE modeling with the three crack types in the underlying HMA: (a) AC overlay over HMA with full-depth crack; (b) AC overlay over HMA with partial top-down cracking; and (c) AC overlay over HMA with partial bottom-up crack.

Based on the FE results (Figure 4.6), for the full-depth crack and partial bottom-up crack, higher stress and strain concentration are developed at the bottom of the cracks than the top because the cracks is located on top of base layer which is weaker and more deformable than the HMA layer. The full-depth crack and the partial bottom-up crack can have higher deformation and higher stress concentration on the underlying base layer, resulting in higher principal stress and strain at the crack tip (at the bottom of the overlay). On the other hand, for the partial top-down crack, the crack is surrounded by the HMA layer, which is stronger than base and subgrade layers, thus there is less concentrated stress and strain compared to the previous two cases. It can be concluded that the partial top-down cracking is less damaging to the HMA overlay and reflective cracking may be more slowly propagated than the other two crack types.

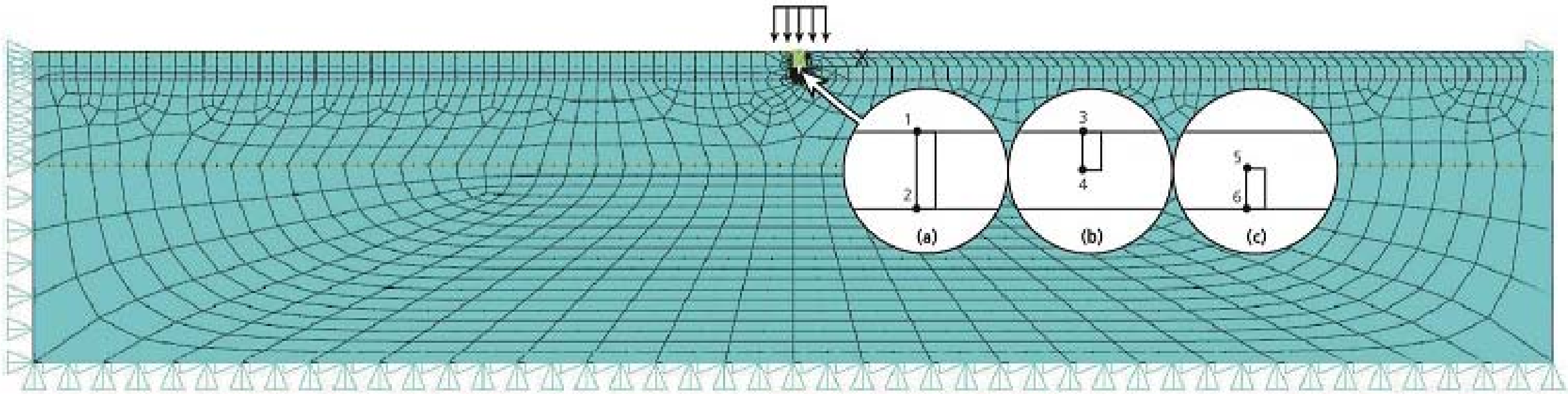
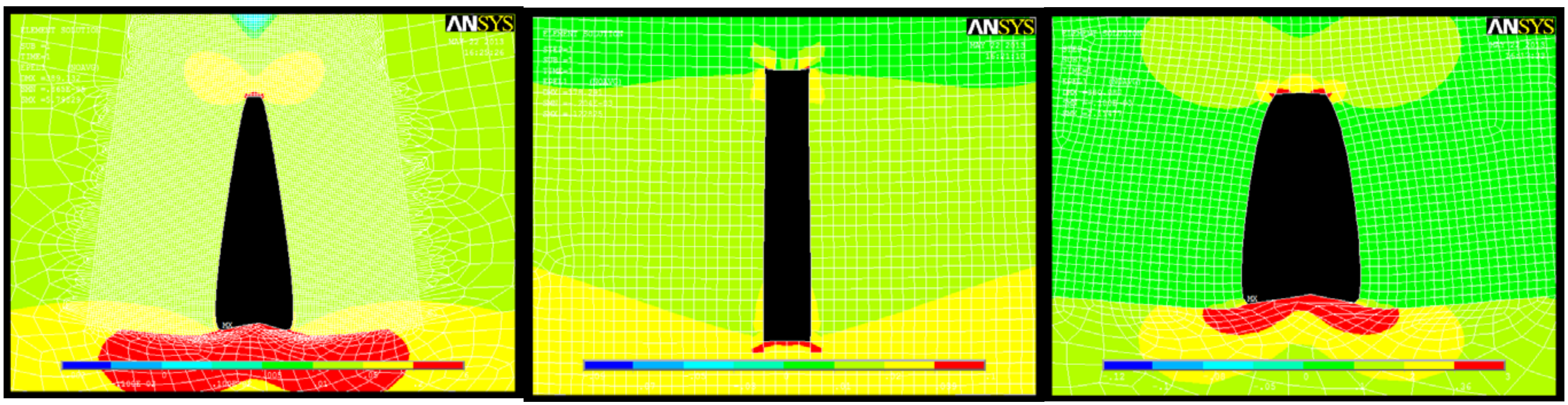


Figure 4.5: FE models showing mesh, boundary conditions, and different types of crack: (a) full-depth crack; (b) partial top-down crack; and (b) partial bottom-up crack.



(a) (b) (c)

Figure 4.6: The contours of principal stress in the vicinity of a crack: (a) AC overlay over HMA with full-depth crack, (b) AC overlay over HMA with partial top-down cracking, and (c) AC overlay over HMA with partial bottom-up crack.

Figure 4.7 presents quantitative values of strain concentration at both top and bottom of the three crack types. The principal strain at Node no. 2 and 6 shows much higher principal strain due to weak support from the base layer. The principal strain at Node no. 1 and 3 shows lower principal strain than that of Node no. 5 because those locations (at Node no.1 and 3) are under high compression along the X and Y-directions. Figure 4.8 indicates quantitative values of shear strain and shear stress at both top and bottom of the three crack types.

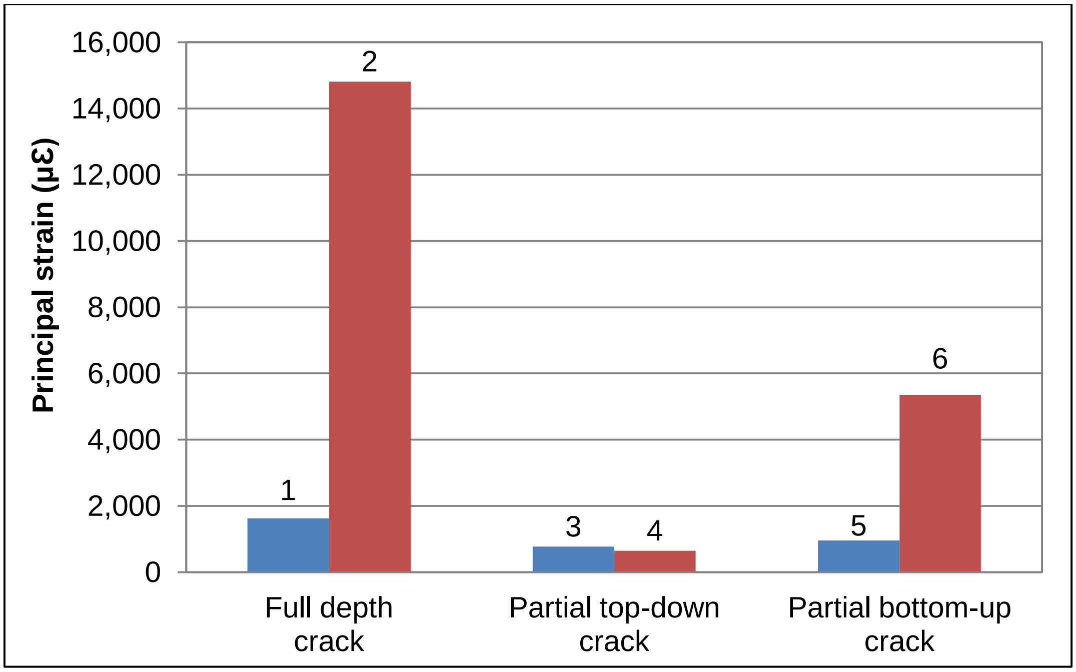


Figure 4.5: Principal strain at the crack tip (of different types of crack condition) with different loading positions.

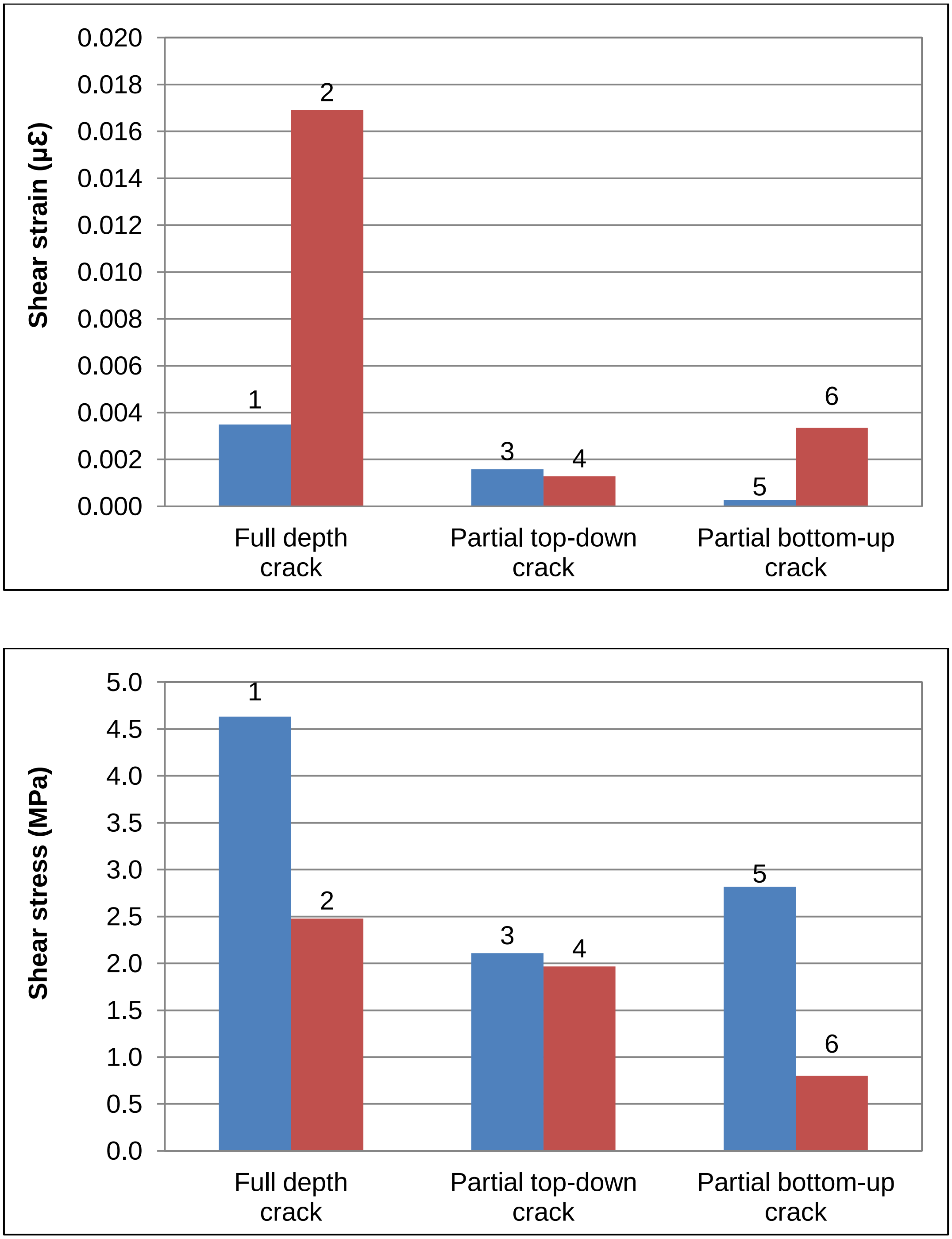
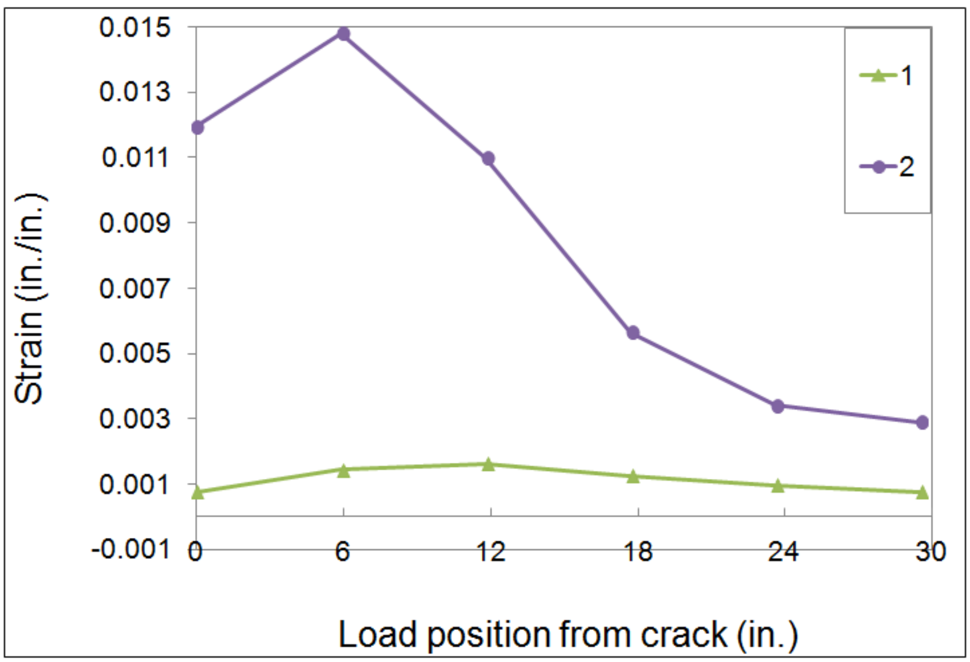


Figure 4.6: Comparisons of (a) shear strain and (b) shear stress at the crack for each cracking condition.

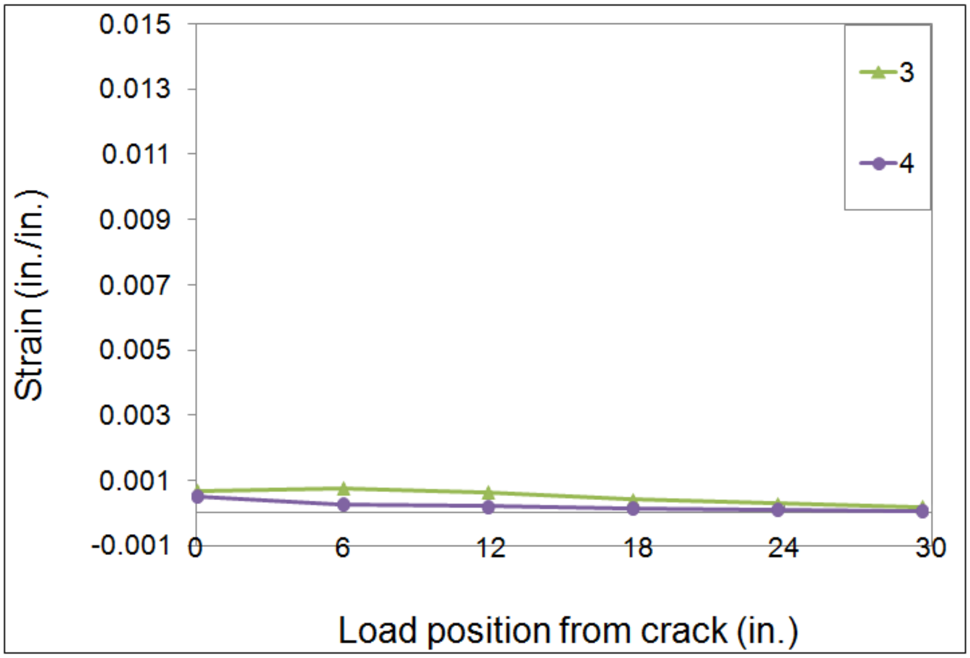
4.4.2. Effect of Different Loading Positions

In order to evaluate the influence of loading position on the behavior of cracking under the three cracking conditions, a "moving load" was simulated by moving the loading point along the pavement with 6-in. intervals. The wheel load was modeled with proper tire-contact pressure; a rectangular contact area of 12 in. (length) by 8 in. (width) with a pressure of 87 psi (600 kPa) was used to simulate the static loading. The width and depth of cracks are same as the previous static case (see Figure 4.5).

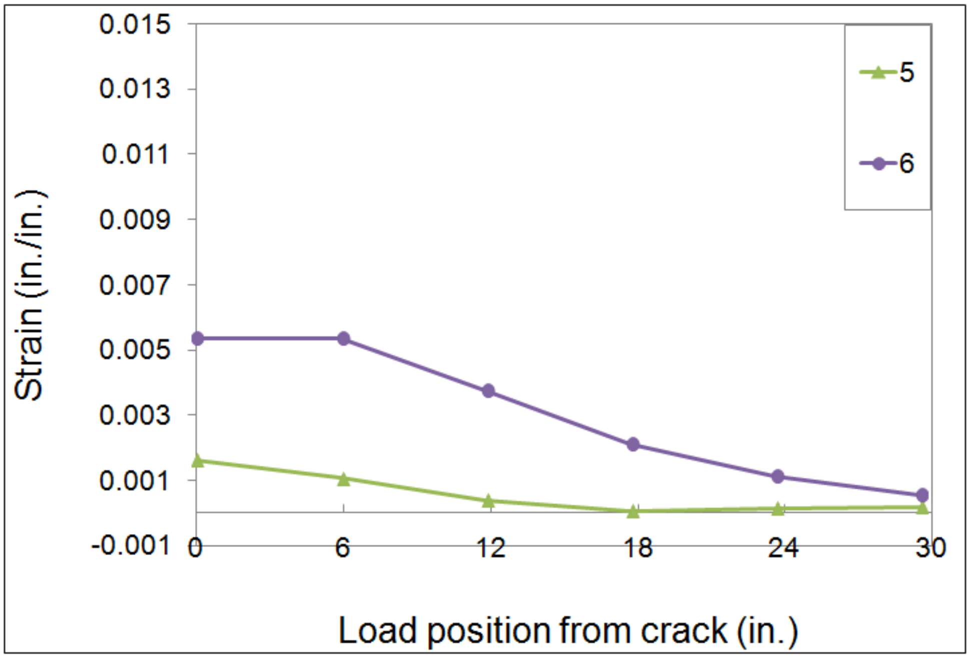
To evaluate the pattern of crack initiation, both top and bottom of the crack were selected for strain measurement. At node numbers 1 and 2 for the full-depth crack, node numbers 3 and 4 for the partial top-down crack, and node numbers 5 and 6 for the partial bottom-up crack (see Figure 4.5), principal strain under the varied loading positions were measured. Figure 4.9 shows the principal strain values with the varied loading positions for each crack condition. The results show that the top-down crack induces much smaller principal strain at the tip of crack, resulting in less damage in the overlay. Another observation is that loading began affecting the behavior of the crack from about a 2 ft. distance.



(a) Full-depth crack



(b) Partial top-down crack



(c) Partial bottom-up crack

Figure 4.7: Principal strain at the top and bottom of crack for the three different crack types

4.4.3. Effect of Different Reflective Cracking Mitigations

The influence of different reflective cracking mitigation methods on crack behavior were studied with the FE simulations. Top-down cracks are common in Florida and these cracks can be partially remained if the crack depth is greater than a mill depth. In addition, full-depth cracks may not be completely removed if the existing pavement is thicker than the milling depth. Thus, the pavement models in FEM contain partial top-down cracks in the existing HMA with the overlay. The three mitigation methods evaluated in the FE study were the mill and inlay, fabric, and ARMI. Three pavement structures were modeled, including the overlay only, the overlay with an ARMI, and the overlay with fabric. The effectiveness of each mitigation method was investigated with respect to principal strain in the tensile direction at the crack. Table 4.2 shows the input values for the three cases; thickness of inlay is 3 in., and those of ARMI and fabric are 0.5 and 0.25 in., respectively.

To investigate the strain concentration developed in the crack, a vertical crack was located on the top of the underlying layer (see Figure 4.10). The width and depth of crack are 0.15 in. and 1 in., respectively. To evaluate the pattern of crack initiation based on strain concentration, 4 locations in the crack (node numbers 1, 2, 3, and 4 seen in Figure 4.10) were selected for the strain measurements under varied loading positions. To consider the tire contact pressure, a rectangular contact area of 12 in. (length) by 8 in. (width) with a pressure of 116 psi (800 kPa) was used to simulate the load. Figure 4.10 shows the element mesh, boundary conditions, and partial top-down crack with 4 points have been modeled.

Through the FE simulations, the change of strain at Nodes 1, 2, 3, and 4 in the crack were measured. Only the principal stress and strain at node 1, which are the key parameters affecting the behavior of the crack, are presented herein. The analysis results at nodes 1, 2 and 3 are presented in Figures 4.10, 4.11 and 4.12, respectively. At the interface between the overlay (or fabric and ARMI) and the underlying pavement, nodes 1 and 2 are shared by both upper and lower layers that are the new overlay and the old cracked-surface HMA, respectively. In other words, the upper and lower sides of Nodes 1 and 2 represent the behavior of new overlay and old HMA, respectively. Due to the difference in materials as well as the location of the crack, stress and strain measurements show different values in the upper and lower sides of the interface. Thus, the results are separately presented for the upper and lower sides of the interface at node 1 as seen in Figures 4.13 and 4.14.

Figures 4.13 and 4.14 summarize the principal stress and strain of the upper and lower sides of the interface, respectively, for the three mitigation methods. For the lower side of the interface, the fabric exhibits the lowest values of principal stress and strain, while the mill and inlay and ARMI follow in order (see Figure 4.13). The fabric is softer and more flexible than the other two materials, and absorbs shear stress/strain induced by a wheel load at the interface, resulting in lower stress concentration and strain development at the tip of crack. However, the fabric can create higher principal stress and strain in the upper side of the interface due to the large horizontal deformation along the plane of fabric. Figure 4.14 shows the principal stress and strain at node 1 in. the upper side of the interface. In the mill and inlay option, this point is at node 1 but represents the upper layer (the AC overlay). Unlike the results in Figure 4.13, the fabric produces the highest principal stress and strain while the mill and inlay causes the lowest stress/strain concentration.

The FE results indicate that the use of a soft interlayer can cause reduced stress and strain at the tip of crack; however, due to large horizontal deformation of the soft interlayer, larger tensile strain at the bottom of AC overlay may occur. Thus, with the paving fabric, sufficient thickness of overlay will be required to avoid premature failure of the pavement through a fatigue-related mechanism. The ARMI is stiffer than fabric and less stiff than a typical AC overlay; thus, its performance is intermediate.

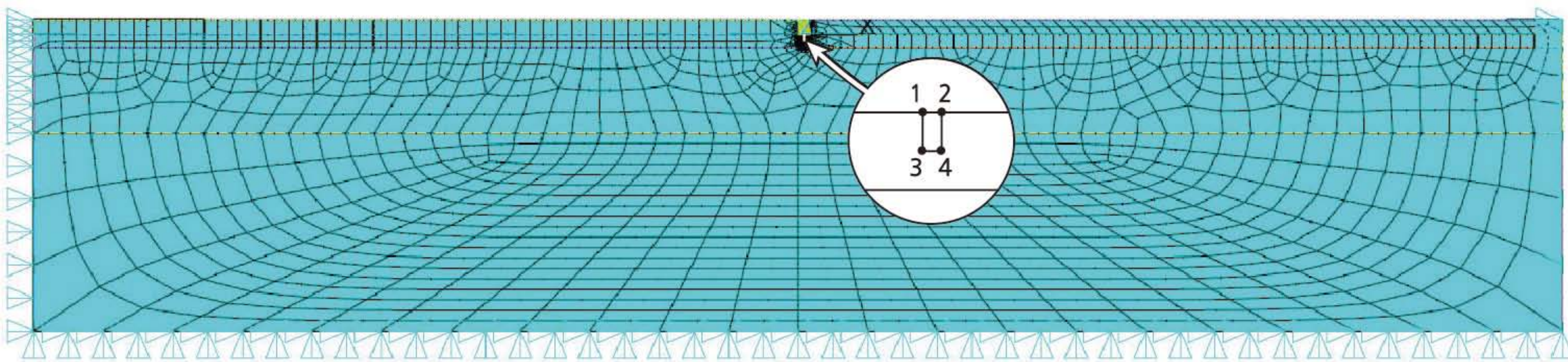
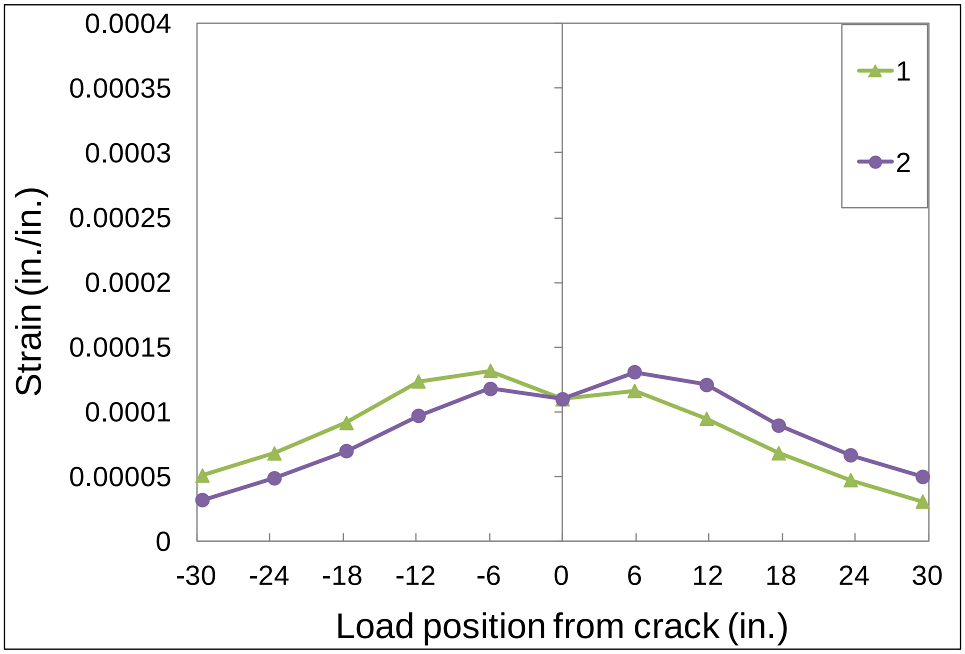
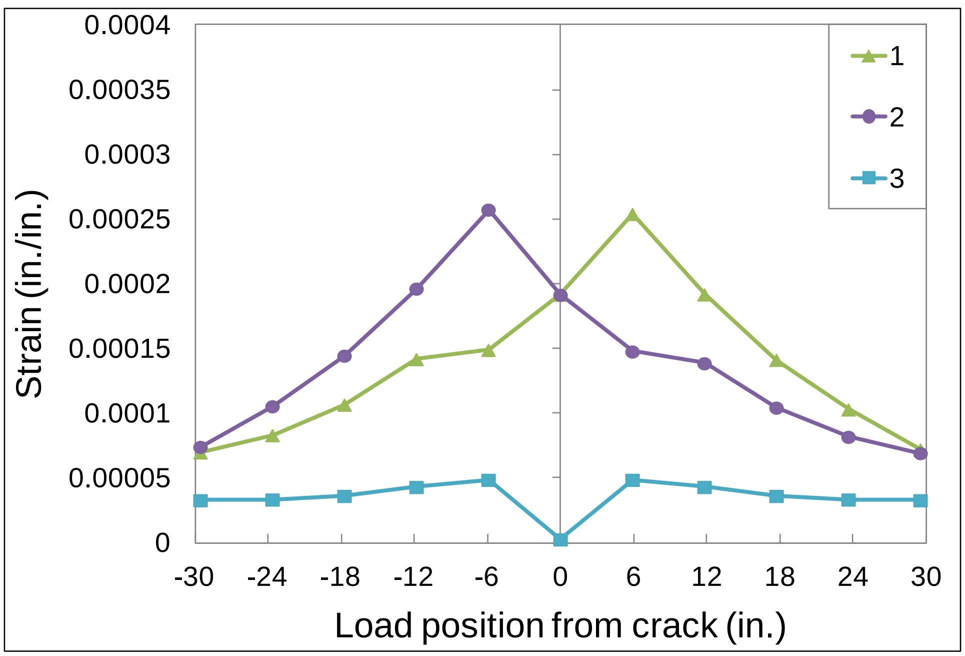


Figure 4.8: FE models showing mesh, boundary conditions, and partial top-down crack for the analyses of three different mitigation methods

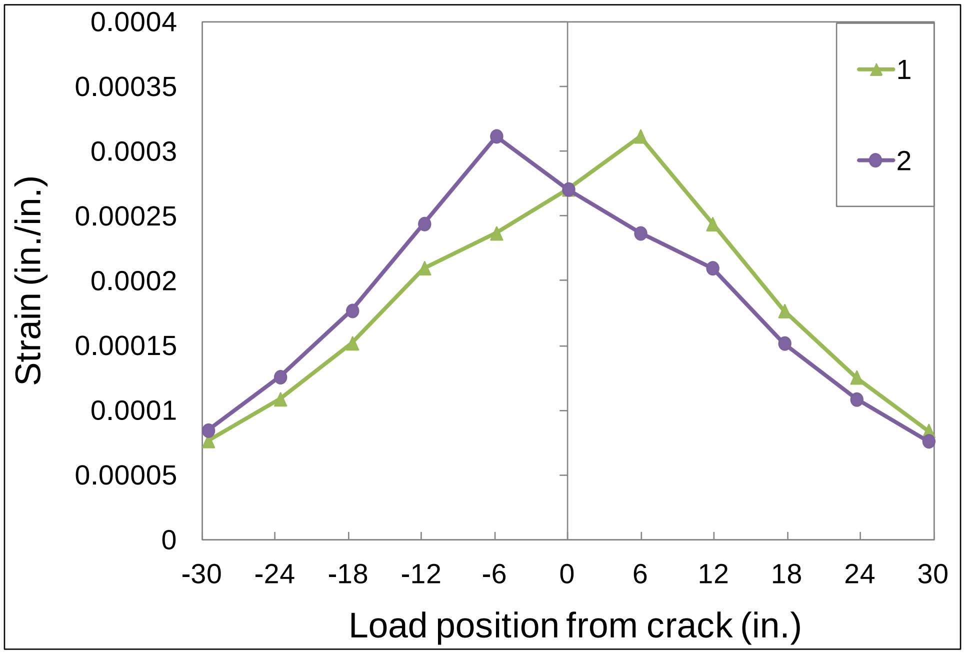


(a) Upper side of the interface

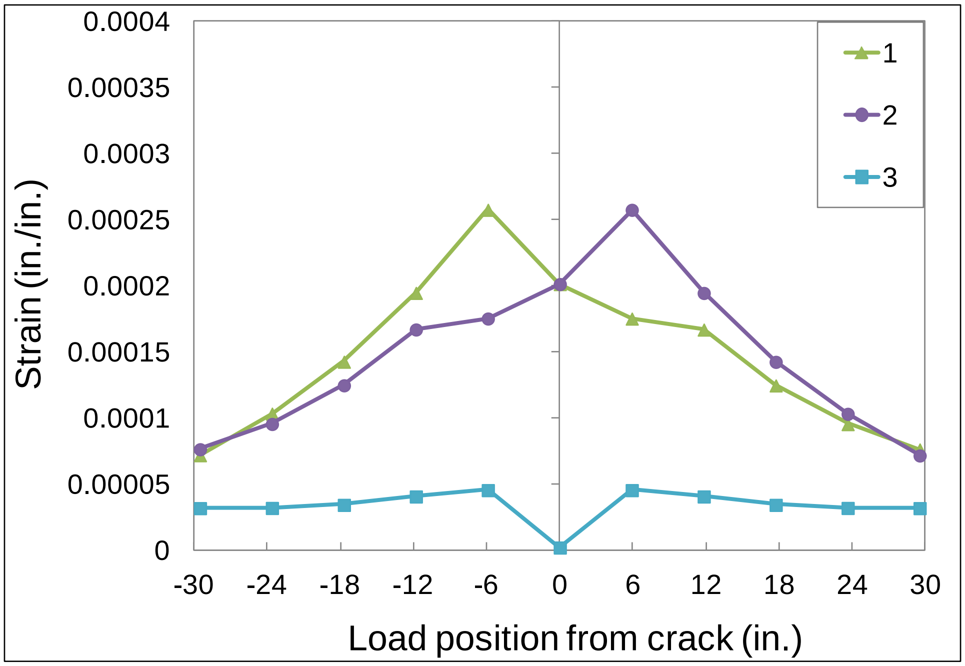


(b) Lower side of the interface

Figure 4.9: Principal strain for the mill and inlay: (a) upper side and (b) lower side of the interface.

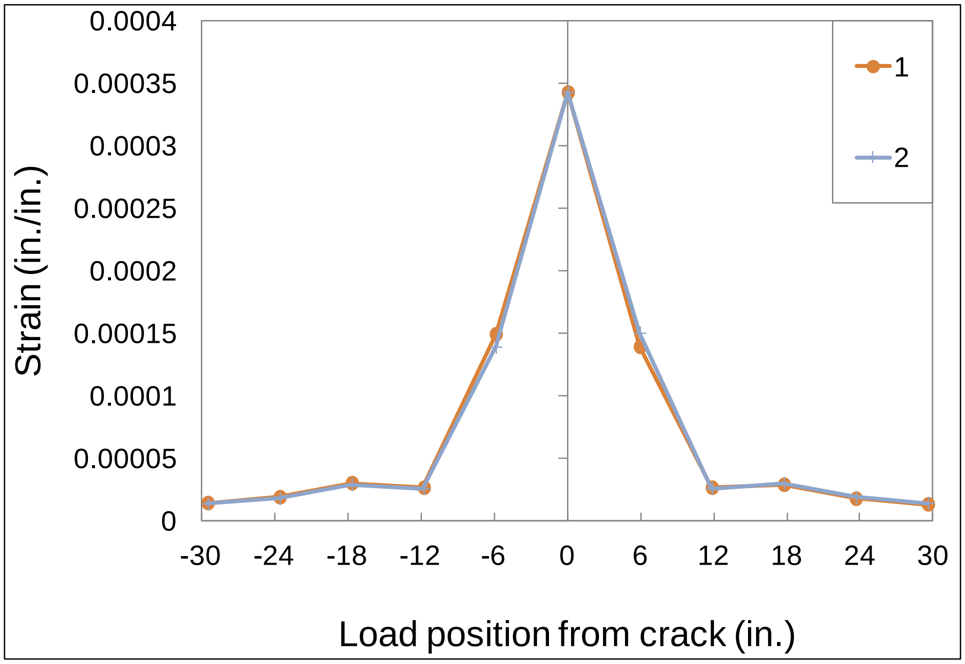


(a) Upper side of the interface

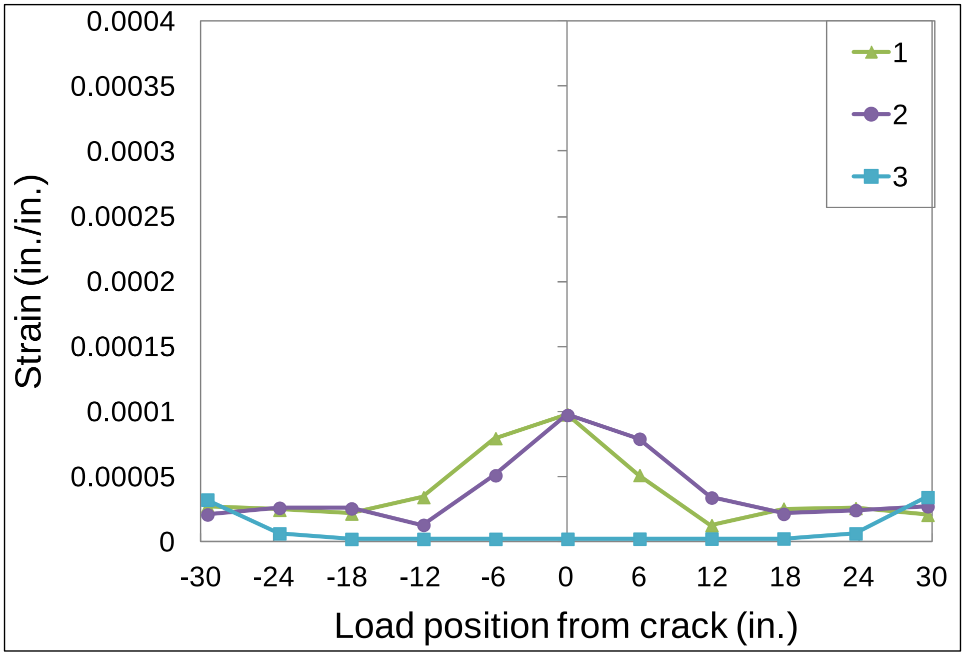


(b) Lower side of the interface

Figure 4.102: Principal strain for the ARMI (a) upper side and (b) lower side of the interface.

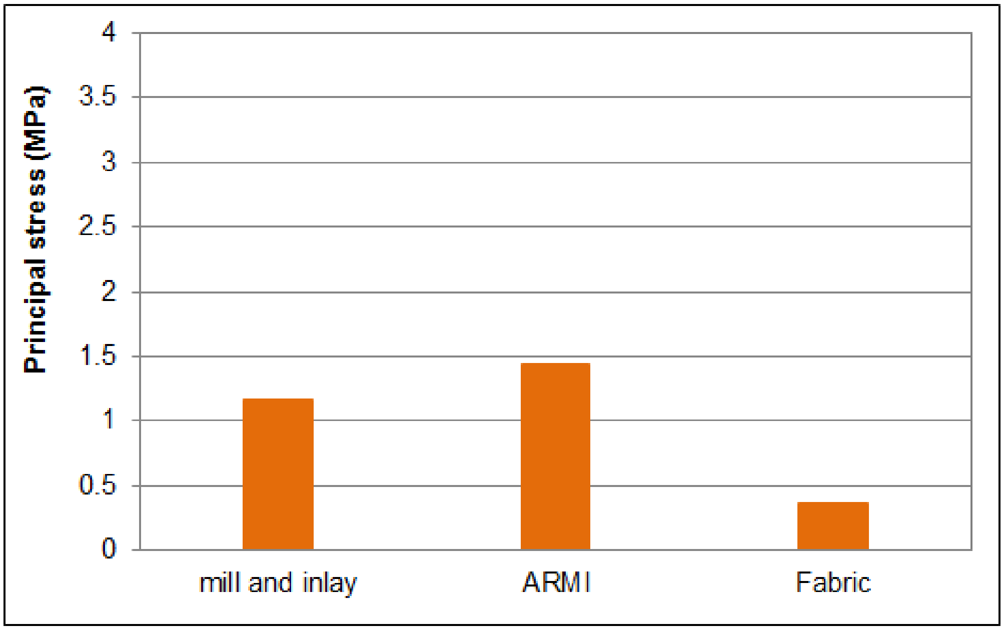


(a) Upper side of the interface

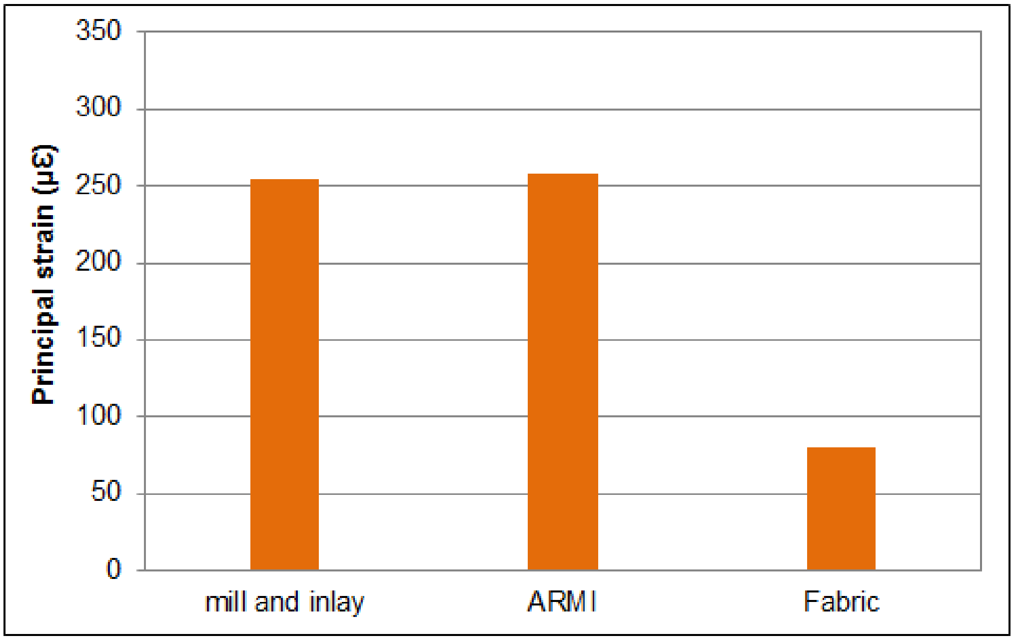


(b) Lower side of the interface

Figure 4.113: Principal strain for the paving fabric (a) upper side and (b) lower side of the interface.

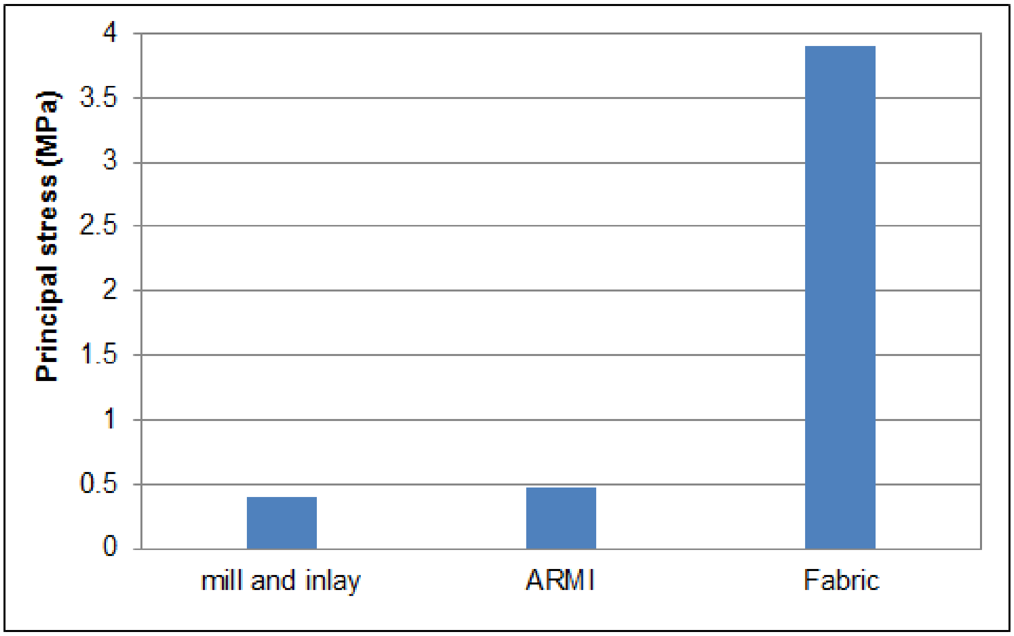


(a) Principal stress

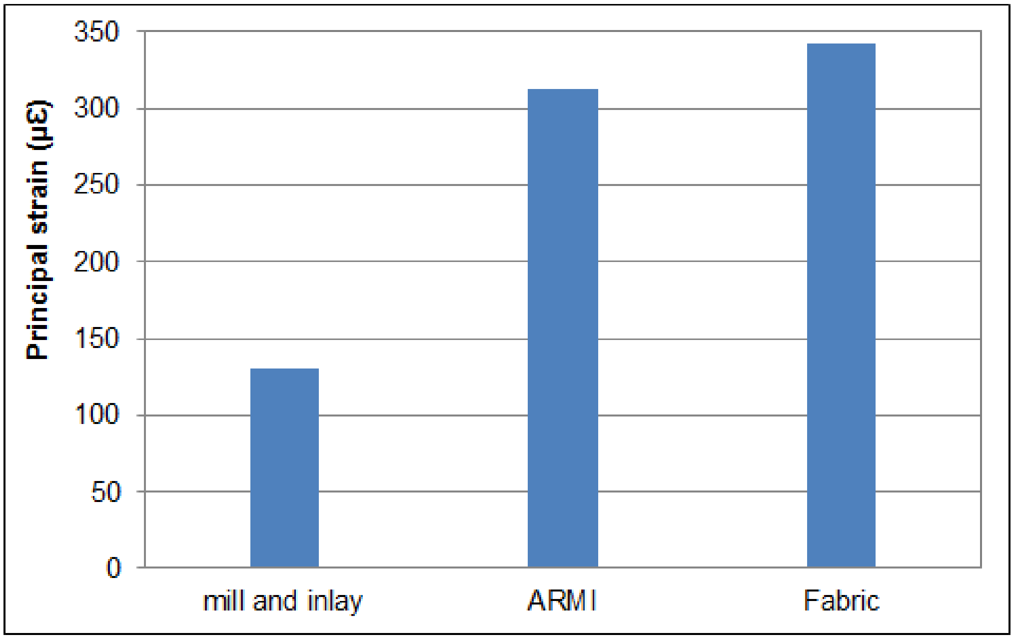


(b) Principal strain

Figure 4.12: Principal stress and strain at Node 1 (lower side of the interface) for the three RC mitigation methods.



(a) Principal stress



(b) Principal strain

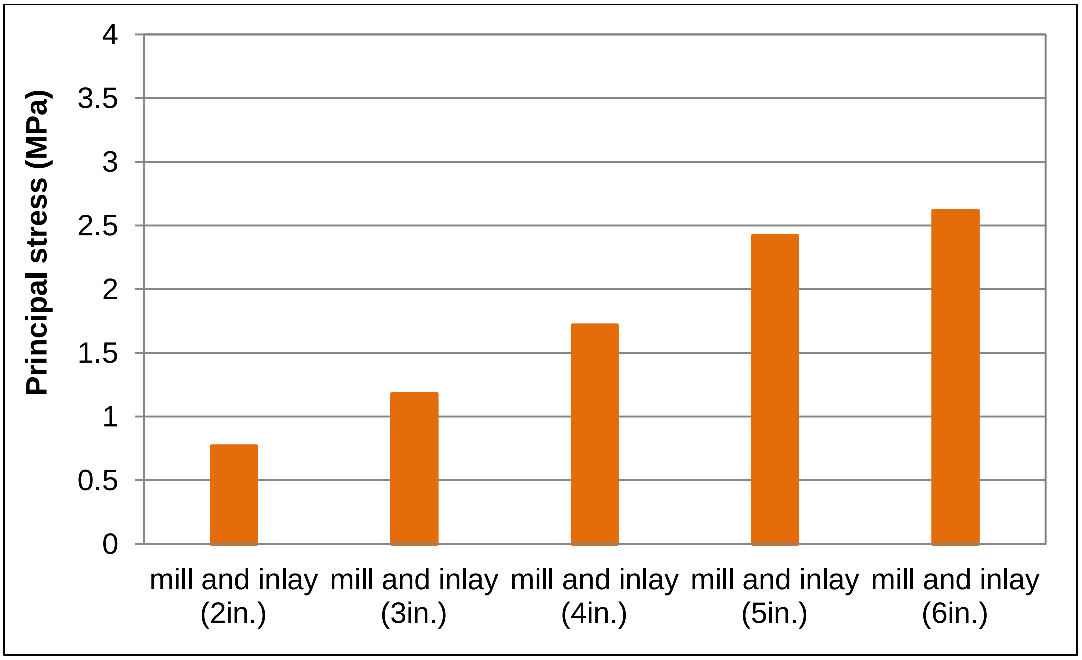
Figure 4.13: Principal stress and strain at Node 1 (upper side of the interface) for the three RC mitigation methods.

4.4.4. Effect of Overlay Thickness in the Mill and Inlay Method

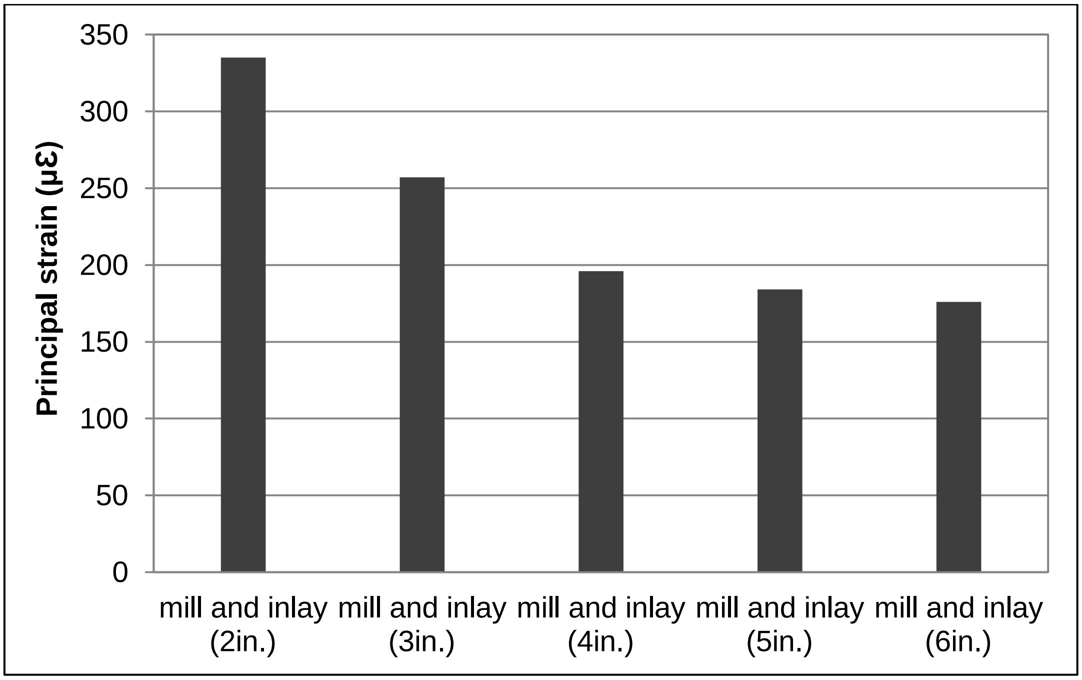
To evaluate the effect of overlay (or inlay) thickness for the mill and inlay option, various thicknesses of overlay were modeled with the same mill depth (3 inches) in this FE study. Material properties were same as the previous case of the mill and inlay (Table 4.2). Different overlay thicknesses of 2, 3, 4, 5, and 6 inches were chosen to compare the change of principal stress and strain.

The results of FE simulation showed that an increase of overlay thickness reduced the principal strain at the vicinity of the crack tip. Figure 4.16 shows that the principal strain at node 1, shown in Figure 4.10, which is the tip of crack located on top of the underlying HMA, decreased proportionally to the overlay thickness. The results shown in figure 4.16 show that the principal strain decreased by more than 42% when the overlay thickness was increased from 2 in. to 4 in.; the principal strain decreased by about 24% with a further increase in the overlay thickness from 3 in. to 4 in. However, the reduction of principal strain become almost zero after 5 in. of an overlay. That is, the benefit of the increased overlay thickness can be limited to 5 inches. The pattern of the strain decrease in the upper side of the interface was the same as the one observed in the lower side of the interface (see Figure 4.17).

For the principal strain, a predominant factor is shear strain compared to X- and Y-direction strains. The critical location for shear stain was found at the edge of the loading area (6 inches offset from the tire edge). For the edge loading case, the shear strain at the crack tip was almost 10 times bigger than X- and Y-direction strains. On the other hand, for the principal stress, the predominant factors are X- and Y-direction stresses compared to shear stresses. Depending on the overlay thickness, the X-direction stress was double or the same as the shear stress. When the overlay thickness is 2 inches, X-direction stress was double the shear stress. On the other hand, the X-direction stress was same as the shear stress when the overlay thickness is 4 inches. The principal stress in the tensile direction is determined by the sum of shear stress and horizontal and vertical tensile stresses. However, the X- and Y-direction compression stresses causes a reduction in the principal stress when the overlay thickness is decreased.

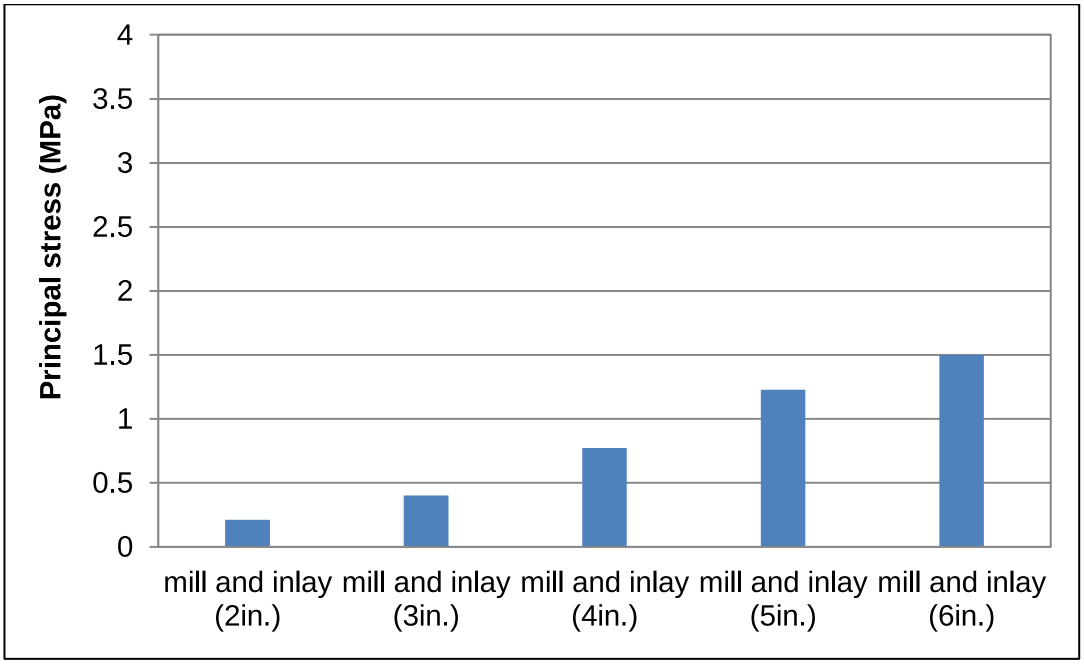


(a) Principal stress

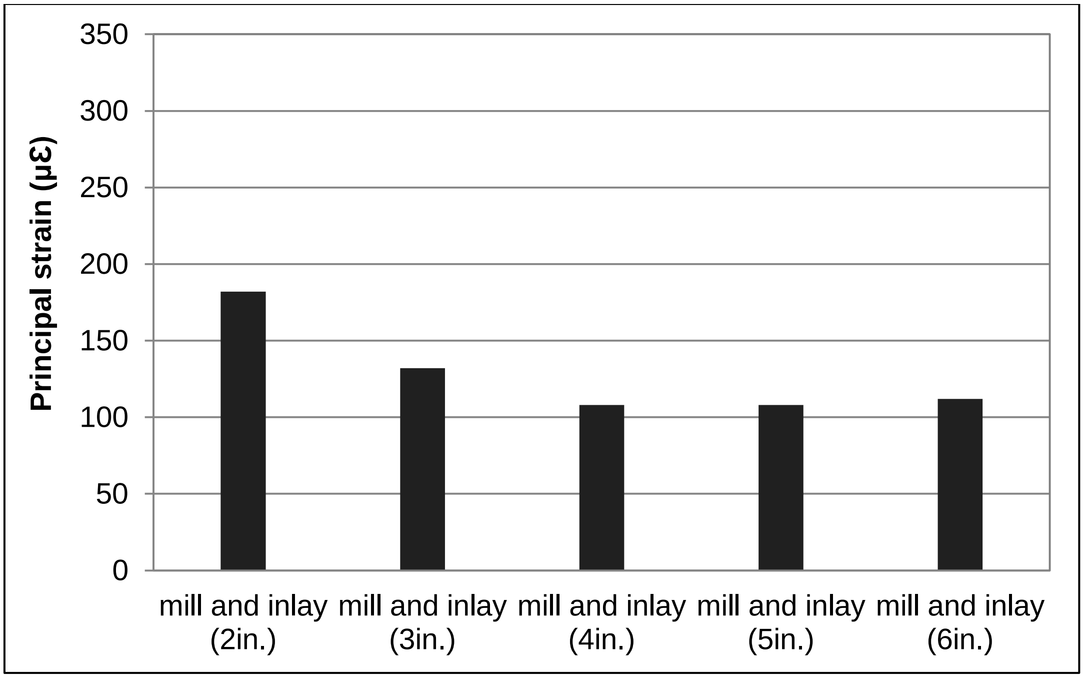


(b) Principal strain

Figure 4.14: Principal stress and strain at Node 1 (lower side of the interface) for the varied thickness of mill and inlay.

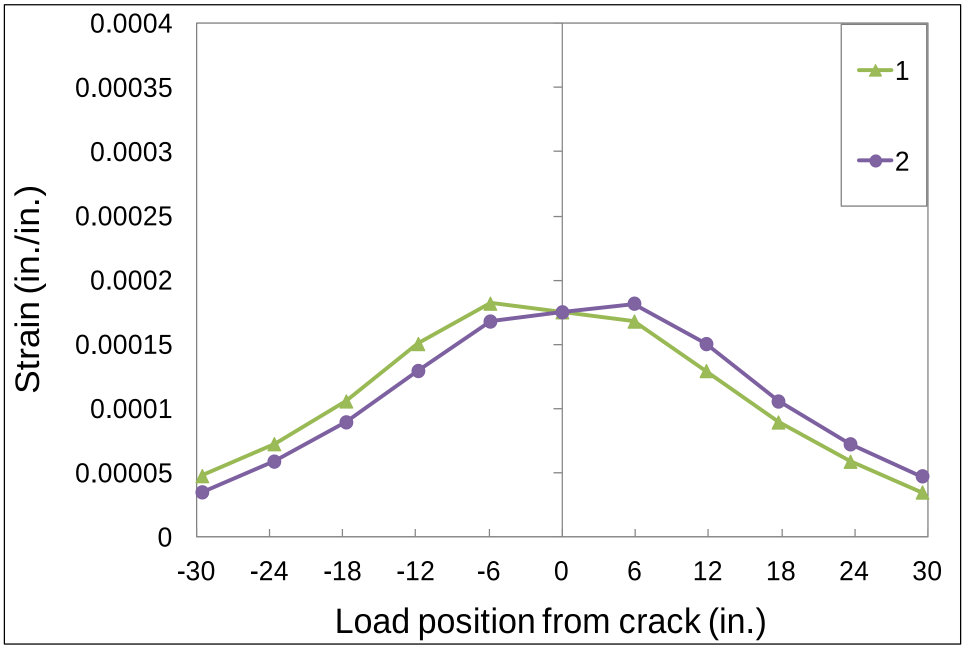


(a) Principal stress

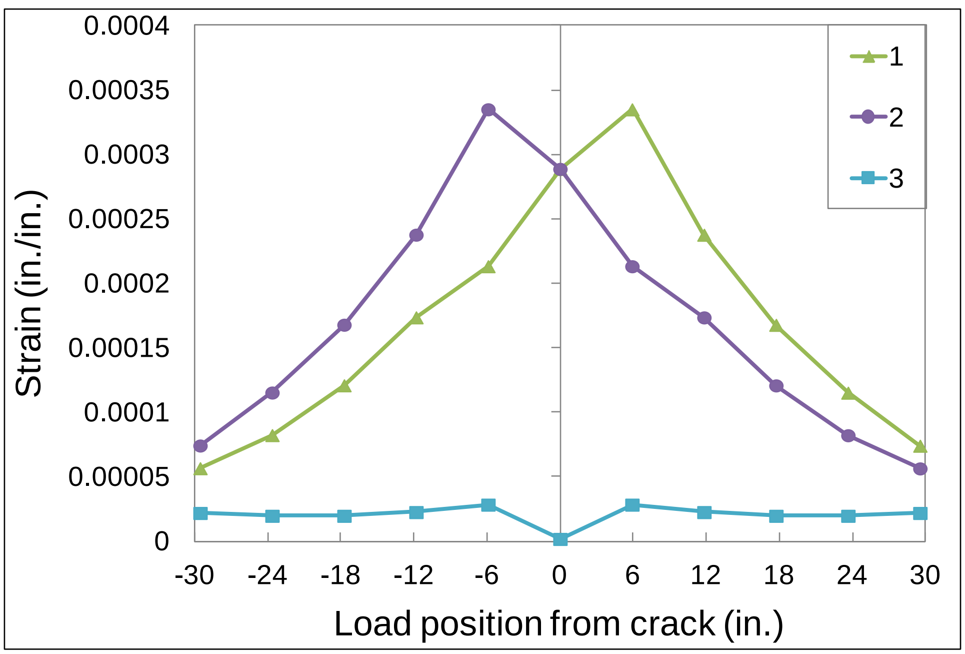


(a) Principal strain

Figure 4.15: Principal stress and strain (upper side of the interface) at Node 1 for the varied thickness of mill and inlay.

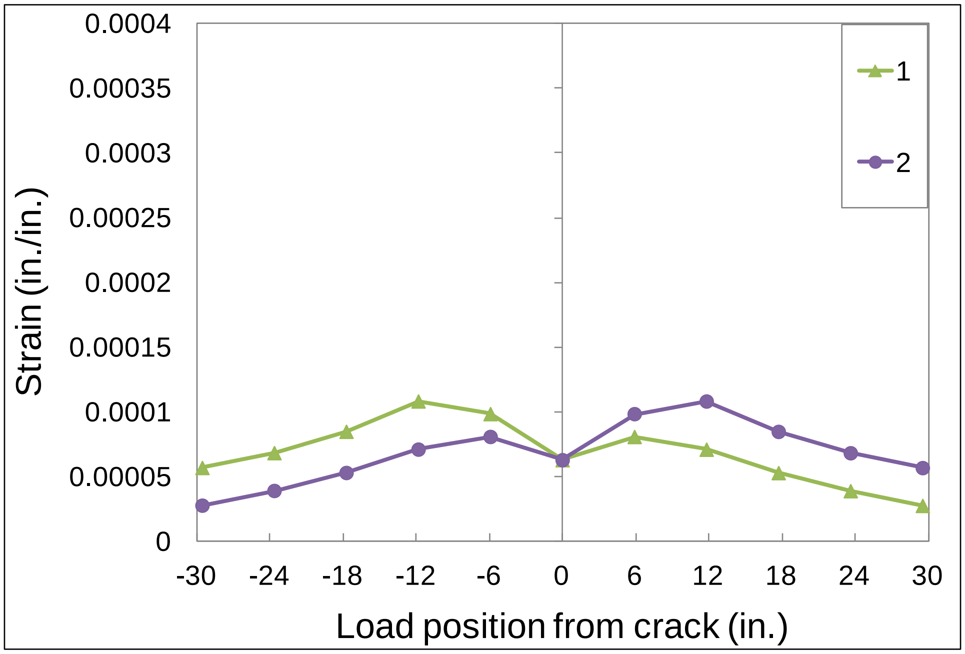


(a) Upper side of the interface

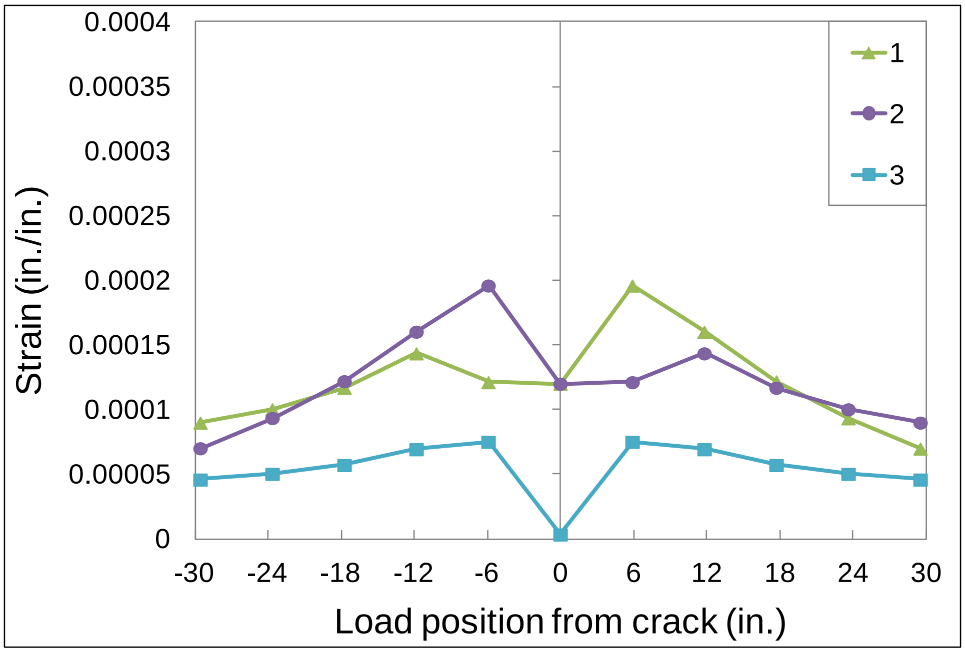


(b) Lower side of the interface

Figure 4.16: Principal strain for the 2-in. mill and inlay (a) in the upper side and (b) lower side of the interface.



(a) Upper side of the interface



(b) Lower side of the interface

Figure 4.17: Principal strain for the 4-in. mill and inlay (a) in the upper side and (b) the lower side of the interface.

4.5. Conclusions and Recommendation

The numerical analyses have provided several key findings to understand the mechanism of reflective cracking in AC overlays of HMA. 2-D finite element (FE) models were developed to evaluate (1) the effect of different crack types in the underlying layer, (2) the effectiveness of different reflective cracking mitigation methods, and (3) the effect of increased overlay thickness. According to the results of FE analyses, the following conclusions have been made.

- Top-down cracking common in Florida may remain in the underlying layer. Compared with full-depth and bottom-up cracks, the top-down crack may cause the least damage to the overlay under traffic loads.

- Fabric can be effective in absorbing tensile and shear stress at the tip of crack in the existing pavement. However, the flexibility of fabric can cause large horizontal deformations in the fabric plane; thus, the potential of crack initiation at the bottom of the AC overlay can be a concern under repeated traffic loads. The crack in the underlying layer may not propagate vertically through the fabric but large horizontal deformation of the fabric can create crack development at the bottom of the overlay which may propagate through the overlay.

- Results of the FE analyses indicated that the ARMI is an intermediate method, but the low stiffness of ARMI layers can cause some deformation issues such as rutting.

- Increased thickness of the overlay would be more effective in mitigating reflective cracking because stress concentration and tensile-strain developed at the bottom of the overlay are the lowest.

- The principal strain at the tip of the crack in both upper and lower sides of the interface decreases proportionally as the overlay thickness increases. When the overlay thickness increases from 2 to 4 in. and from 3 to 4 in, the principal strain decreases around 40% and 25%, respectively.

As future research in the numerical study, the authors recommend the following topics to be further explored.

- The effect of thermal loading also needs to be investigated. In Florida, low-temperature cracking may not be a significant concern for asphalt pavements. However, daily temperature change causing repetitions of pavement horizontal movements at cracks can accelerate damage in the overlay because of a higher coefficient of thermal expansion (CTE) of HMA than that of PCC [60, 61]. In addition, material aging due to weathering can be also incorporated into the FE analysis.

- Many currently available reflective cracking mitigation methods are interlayer systems such as fabric, ARMI, ISAC, SAMI, and chip seal. The bonding condition in the interface would significantly affect the behavior of reflective crack in the AC overlay; however, their bonding conditions have not been well studied. FE models that take into account actual bonding conditions can better predict the performance of interlayer-type mitigation methods associated with reflective cracking.

5. DETERMINATION OF PERFORMANCE GOAL

5.1. Introduction

Over the last two decades, a number of RC mitigation methods have been introduced to retard reflective cracking. The primary purpose of this research is to identify the most effective RC mitigation method considering Florida's conditions. Determining the performance goal of each RC mitigation method is one key input for the LCCA in Chapter 6 and the MCDM analysis in Chapter 7. In this report, the performance goal is defined as the expected field performance (or life expectancy) in the unit of years. Thus, the authors have collected data showing the field performance of RC mitigation methods based on the literature review, manufacturer's inputs, and response of each SHA. The performance of those methods varies from state to state.

5.2. Data Collection for Performance Goal

5.2.1. Performance Expectations from the Nationwide Survey

A nationwide survey was conducted by distributing the questionnaire to all state agencies in the United States. Findings of the survey were summarized in detailed in Chapter 2 and the field performance goal of the selected RC mitigation methods were presented in Table 2.6. A summary of Table 2.6 is presented for the comparison with findings from the literature review and manufacturer's experiences.

For the survey, the authors received 18 responses from all SHAs in the U.S. All of the responding SHAs expected that RC would not appear within the first year of construction. Only two SHAs, Washington and Nevada DOTs, expected that their roads would last longer than 4 years without significant RC. Another important question in the survey was about a typical thickness of overlay used by the agencies. The survey result showed that the typical asphalt overlay thickness is between 1 and 2 inches, and the performance expectations were about 2 to 4 years without RC mitigation methods after the placement of overlay.

The agencies were also asked about their most successful RC mitigation method and its field performance. Two agencies responded that the most successful RC mitigation method was fabric (geotextiles), but the performance varies; one agency expected RC to appear after 4 to 5 years, and the other expected it after 5 years. An increase of overlay thickness was chosen by 6 agencies as their most successful method. Three agencies chose a crack-arresting layer (e.g., unbound aggregate layer), and the performance varied from 2 to 5 years. Specifically, Montana DOT recommended a cold in-place recycling (CIR) before overlaying with a crack-arresting layer. Two of the agencies selected a stress-absorbing membrane interlayer (SAMI) and expected RC to occur after 2 to 5 years. Idaho DOT found that reinforcing HMA (e.g., fiberglass or geogrid) performed best and the expected performance was from 4 to 6 years. Iowa DOT found

Strata to be the most successful.

The survey results also indicated that 12 out of 18 respondents did not have established criteria to determine whether a selected RC mitigation is successful. Six SHAs currently utilize the criteria as summarized in Table 5.1. Table 5.1 also includes the most successful RC mitigation methods the six states selected.

Table 5.1: Criteria for a successful reflective cracking mitigation method.

State	**What constitutes criteria for a successful reflective cracking mitigation method?**	**Most Successful RC Mitigation Method**
Alaska	50% of the reflective cracks appear after two years	Paving fabrics/geotextiles
Idaho	Double the time between the mitigation section and a control section as to when reflective cracks reappear.	Reinforced HMA overlay (i.e., geogrids, steel, fiberglass)
Arkansas	30% or less in 3 years	None
Saskatchewan, Canada	No cracks for three consecutive winters.	No Response
Nevada	Minimal cracking after 5 years	Crack-arresting layer
Massachusetts	80% of cracks delayed for 5 years.	Milling, SAMI + Thicker Overlay

5.3. Performance for RC Mitigation

In this section, performance expectations for RC mitigation methods were determined based on literature reviews, survey, and interviews with industry experts. Performance expectations of RC mitigation methods vary greatly amongst literature, agencies, and industry experts. Currently there is no general rule to evaluate the effectiveness of a number of RC mitigation methods. There are numerous variables that affect the performance of pavement structures. Therefore, the performance of RC mitigation methods should be relative to the performance of control sections for specific projects or regions with similar underlying conditions. For example, there are studies claiming that an interlayer system doubles the performance life of a pavement when compared to a control section. This comparison can be used in determining the performance, and a relative life cycle cost analysis (LCCA) can be performed by comparing the mitigation method relative to the control section. Other studies compare the performance of an interlayer with a certain thickness of an asphalt overlay. This comparison can be also used to determine the performance of interlayer systems.

Currently, a majority of SHAs do not have the standard to rate the performance of RC mitigation methods. In this study, the criterion of field performance was defined as the performance difference in the unit of years at 50% of RC between a pavement section with a specific mitigation method and a control section. In other words, the performance difference equals the time of 50% RC for the treated section minus the time of 50% RC for the control section. For example, SHAs can perform a detailed crack map prior to the overlay (or after milling) and monitor the onset of RC at the locations where existing cracks are; thus, the percentage reflective cracking can be calculated. This performance criterion is graphically explained in Figure 5.1 as denoted as "X" (or $\overline{CD}$). This approach takes into account for the time to initiate reflective cracking as well as the crack-propagation rate.

Site conditions such as climate, traffic, and road materials are all different; thus, the performance of reflective cracking cannot be simply compared in years without considering those regional road conditions. Therefore, this index takes into account for the retarding of cracking (the onset of RC) as well as the crack deterioration rate. This approach compares the treated sections with the control section (where no treatment) in the same project. The data sets for the control and treated section are mostly taken from published data, unless specific performance expectations are provided by the FDOT experts. The equation below explains the performance measure of each RC mitigation method:

$$X\ (or\ \overline{CD}) = \overline{B0} - \overline{A0} + \frac{50}{b} - \frac{50}{a}$$

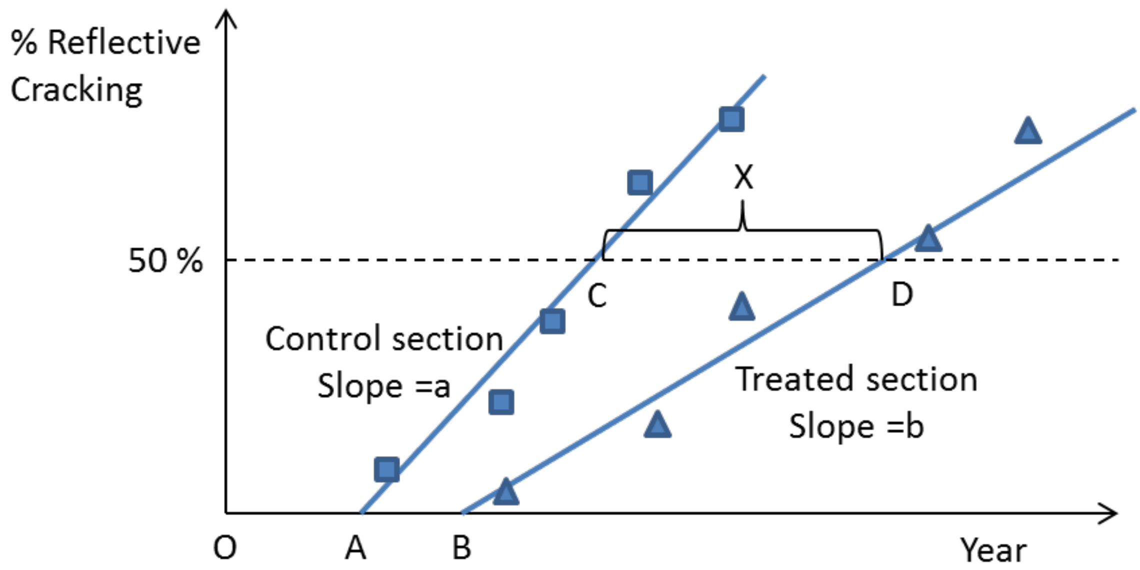


Figure 5.1: A conceptual diagram showing the selection of performance of RC mitigation methods

As mentioned above, in order to find the performance ranges for each mitigation technique, field-performance data of each mitigation method was collected and the experts' opinions were also obtained. Table 5.2 summarizes the performance of the selected mitigation methods at 50 % reflective cracking. The correspondent resources of data for each method are also presented in the table. These performance data were used as inputs for the MCDM analysis, as a separate criterion. However, for the LCCA, the rehabilitation cycle is considered as two times the performance measure. This cycle represents the time that it takes for the cracks to appear 100%, and simultaneously considers the relative performance between treated and control sections. While compared to the time that it takes for the cracks to fully appear in the treated section, this rehabilitation cycle shows a similar range of performance data.

Table 5.2: Performance data as input for the MCDM

Method	Years until 50 % cracks appears after fitted to uncertainty concept		Reference
	Min	Max	
Geosynthetic (Fabric)	3.8	4.9	[7, 19, 21, 33, 62]
Strata	3.6	5.1	[32]
ARMI	2.0	5.0	FDOT Engineers
ISAC	2.7	3.2	[13, 14, 30]
Cold-in-place Recycling	2.3	4.4	[21, 26]
Hot In Place Recycling	2.3	4.5	[26, 63, 64]
Chip seal	2.1	2.9	[21, 31]
Mill and Inlay (3 in)	1.9	2.6	[7, 19, 26]
Mill and Inlay (4 in)	3.1	4.6	[7, 19, 26]

6. LIFE CYCLE COST ANALYSIS

6.1. Introduction

In this chapter, a LCCA was conducted to evaluate cost effectiveness of different RC mitigation methods. In Chapter 5, the author selected eight RC mitigation methods widely used across the country. The selected eight methods are (1) fabric, (2) interlayer stress-absorbing composite (ISAC), (3) chip seal, (4) Strata, (5) ARMI, (6) cold-in-place recycling (CIPR), (7) hot in place recycling (HIPR), and (8) increased thickness of mill and inlay. FDOT's LLCA software customized from FHWA's RealCost software was used in the LCCA. Cost data for each method have been obtained through literature and personal interviews with manufacturers and FDOT's engineers.

6.2. Review on Life Cycle Cost Analysis

LCCA is a tool used to make long-term investment decisions considering cost effectiveness. During the LCCA, all of the costs associated with a project are considered, not just the initial cost but also the likely future costs associated with a project over time. This tool is effective in conveying multiple scenarios of alternative investment to decision makers. The LCCA is defined in Section 303 of the National Highway System Designation Act of 1995 as "(The) process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment (NHS 1995)"

The Federal Highway Association (FHWA) advocates the use of a LCCA to help choose a cost-effective project alternative and to help convey the benefits of the alternative chosen to the public [65]. The FHWA's Life-Cycle Cost Analysis in Pavement Design – Interim Technical Bulletin details the procedure for conducting LCCA of pavement projects. LCCA incorporates discounted long-term agency cost, user cost, other cost, and performance period [66]. The discount rate used for an LCCA can have a significant influence on the final results; an acceptable discount rate for LCCA ranges from 3 - 5%. The user costs are those that are incurred by users traveling on a highway because of detours during construction of projects. Similar costs between alternatives should not be used for LCCA calculations because they will cancel out each other in LCCA calculations, but should be mentioned in the text.

6.3. LCCA Use by State Highway Agencies

The Caltrans Division of Research and Innovation reviewed the LCCA practices of 17 state agencies [67]. The state agencies used either FHWA's RealCost software, AASHTO's DARWin software, or custom in-house software to calculate LCCA for projects. This study found that six state agencies use FHWA's RealCost software, three state agencies have developed custom

LCCA software packages, three state agencies use custom Excel spreadsheets, and five of the state agencies did not specify which LCCA tool is being used. The findings of this study report that FDOT uses the RealCost software, however the FDOT has asked this research team to use a custom Excel software that is based off of RealCost to perform the LCCA.

Parameters used for an LCCA include analysis period and discount rate. The analysis period used to conduct LCCAs ranges from 10 to 50 years and either 40 or 50 years is most commonly used. On the other hand, the discount rate used ranges from 3 to 5 percent and most state agencies use 4 percent. The inclusion of the user cost varies amongst state agencies. Among 17 states reviewed, 9 states include the user cost while 6 states do not and 2 states consider it optional.

The FDOT uses a custom LCCA software based off the FHWA RealCost software. The analysis period used by the FDOT is 40 years, the discount rate is 3.5 and the use of user costs is considered if it will make a significant difference in the analysis [67].

6.4. FDOT's LCCA Software

The LCCA Software customized in FDOT is Excel based and is modified from the FHWA's RealCost software. This software calculates the LCCA of pavement design alternatives. There is a list of typical highway construction pay items and design options that can be used to adjust an analysis within the software. When a typical roadway section is chosen from a dropdown list, the construction pay items are loaded onto various sheets in the Excel workbook. The typical roadway sections vary from rural 2-lane roads to urban 6-lane roads.

A list of construction items is loaded onto the "Unit Prices" sheet. The user of the software inputs mean prices and standard deviation for the prices associated with each construction item. This information is then loaded onto two other sheets which calculate the present worth. One is the "Flexible" sheet for flexible pavements while the other is the "Rigid" sheet for rigid pavements. There is an additional sheet titled "Alternate" that is used to compare additional designs. Information on this sheet is manually inputted. The software generates graphs to compare the flexible and rigid pavement options. Also, a report is generated and it details the difference in costs of the rigid and flexible pavement. A screen shot of the FDOT's custom LCCA software is seen in Appendix B (Figure B.1). This screen shot is of the sheet that is used to calculate the present worth of a flexible pavement. The information from the "Unit Prices" sheet is used on this sheet to perform the calculations.

This software was used to calculate the cost associated with the reflective cracking mitigation methods. The results from the software were then inputted into tables that are in the following sections of the report.

The FDOT's LCCA software was used to calculate the LCCA for the RC mitigation methods.

The software consists of typical roadway types and the pay items of each mitigation method. The cost will be different based on different types of asphalt and friction courses that are used. Therefore, the LCCA is separated into rural and urban highways.

The LCCA in this study was aimed at comparing the cost-benefit of each mitigation method, not to find the actual precise cost of maintenance. In order to analyze the accurate life cycle cost of each method, detailed data of construction and rehabilitation costs as well as the exact time of rehabilitation recurring cycles are needed; however, obtaining itemized data for each of the selected eight RC mitigation methods were unavailable. The used approach is suitable to compare different mitigation techniques based on their approximate life cycle cost, and it can be used as a criterion in the decision making tool. The analysis period in the LCCA has been set to be 20 years, meaning how much the present worth of an annuity would be in order to maintain the roadway for 20 years using the proposed technique.

Typical roadway types are seen in Table 6.1, showing the type of friction course used for rehabilitations on that section and the mean price for the friction course [68, 69]. The mean price was obtained from the FDOT's Specification and Estimates website, where the mean price data are for the year 2012 [69]. The LCCA for each RC mitigation method was calculated for each road type and compared each other in price due to the differences in asphalt and friction course used. Each mitigation method consists of a friction course. The FDOT's Flexible Pavement Design Manual states the type of friction course to be used depending on the design speed and number of lanes [68].

Table 6.1: Roadway sections and friction course [68, 69]

Road Type	**Friction Course**	**Thickness (in.)**	**Mean Price (Ton)**
Rural Arterial/Collector 2-Lane (2-Way)	FC-9.5 Rubber	1	$105.00
Rural Arterial/Collector 4-Lane Divided	FC-5 PG 76-22	0.75	$117.20
Rural Limited Access 4-Lane Divided	FC-5 PG 76-22	0.75	$117.20
Urban 4-Lane Arterial Divided (45 Mph)	FC-12.5 Rubber	1.5	$103.33
Urban 6-Lane Arterial Divided (<45Mph)	FC-12.5 Rubber	1.5	$103.33
Urban 5-Lane Arterial/Collector Undivided	FC-12.5 Rubber	1.5	$103.33

Table 6.2 displays the asphalt type used for the rehabilitation of each road type. This information was obtained from the FDOT's LCCA software. For the mitigation methods that require a layer of asphalt, such as mill and inlay, the following types of asphalt were used for the analysis for the respective road type section. The mean price for this asphalt was also obtained from the FDOT's Specification and Estimates website [69].

Table 6.2: Roadway sections and asphalt type [69]

Road Type	Asphalt Type	Mean Price (Ton)
Rural Arterial/Collector 2-Lane (2-Way)	Type SP Traffic Level C	$83.00
Rural Arterial/Collector 4-Lane Divided	Type SP Traffic Level D PG76-22	$92.68
Rural Limited Access 4-Lane Divided	Type SP Traffic Level D PG76-22	$92.68
Urban 4-Lane Arterial Divided (45 Mph)	Type SP Traffic Level B	$87.28
Urban 6-Lane Arterial Divided (<45Mph)	Type SP Traffic Level C	$83.00
Urban 5-Lane Arterial/Collector Undivided	Type SP Traffic Level B	$87.28

For urban roads, the rehabilitation project may require the final elevation of roads to be repaired same as the elevation of current roads. However, rural roads without bridges and curbs/gutters may be built up depending on the existing conditions, forecasted traffic, and pavement structure. The LCCA was aimed at urban roads; therefore the LCCA included the depth of milling equal to the thickness of the friction course and the layer of asphalt. Table 6.3 shows the milling depth as well as overlay thickness of different methods. Table 6.4 displays the mean price for milling depth that was used to calculate the mill and inlay.

Table 6.3: Milling and overlay thickness used in the LCCA for the different RC mitigation methods

Method	Milling Depth (in)	Thickness of method (in)	Inlay/Overlay thickness (in)
Geosynthetic (Fabric)	3	<1	2
ISAC	3	0.15	2
Chip seal	3	0.75	2
Strata	3	1	2
Cold-in-place Recycling	---	2	2.5
Mill and Inlay (3 in)	3	3	3
Mill and Inlay (4 in)	4	4	4
ARMI	3	0.5	1.5-2
Hot In Place Recycling	---	2	2.5

Note: In this study, a typical mill and inlay is considered as a control section

Table 6.4: Mean price for different milling depth (FDOT 2013)

Milling Depth (Inch)	Mean Price ($/Sq.Yd)
1	1.49
2	1.52
3	1.87
4	2.11
5	3.35
6	8.85

6.5. Results of LCCA for the Selected RC Mitigation Methods

6.5.1. Mill and Inlay (3 inches)

The input data used to calculate the LCCA for the mill and inlay was obtained from historical cost information from the FDOT's Specifications and Estimates website [69]. Annual state wide averages for construction items in 2012 were used. Then the LCCA for each typical road section was calculated based on the identified milling depth and overlay thickness that are indicated in Table 6.3.

The crack propagation through the HMA overlay is assumed based on the obtained performance data. Performance data of different methods are explained in detail in performance section. The results for the analysis are presented in Table 6.5 and Table 6.6. The present worth was calculated with the FDOT custom LCCA software and was divided by the number of lanes to obtain the cost/lane mile. The analysis was performed for the minimum and maximum expected performance. The annual worth was then calculated to obtain the annual worth per lane mile. This analysis was performed for six different road types. The annual worth ranged from $22,669 /lane mile to $36,035/lane mile.

Table 6.5: Mill and inlay (3 inches), discount rate 3.5% - maximum range

Road Type	Analysis Period (years)	Performance (years)	Mill Depth (in)	Overlay Thickness (in)	Present Worth ($)	Present Worth ($/lane mile)	Annuity ($/lane mile/year)
Rural Arterial/Collector 2-Lane (2-Way)	20	5.2	3	3	$322,664	$322,664	$22,669
Rural Arterial/Collector 4-Lane Divided & Rural Limited Access 4-Lane Divided	20	5.2	3	3	$346,422	$346,422	$24,338
Urban 4-Lane Arterial Divided (45 Mph)	20	5.2	3	3	$435,095	$435,095	$30,568
Urban 6-Lane Arterial Divided (<45Mph)	20	5.2	3	3	$355,549	$355,549	$24,979
Urban 5-Lane Arterial/Collector Undivided	20	5.2	3	3	$422,664	$422,664	$29,694

Table 6.6: Mill and inlay (3 inches), discount rate 3.5% - minimum range

Road Type	Analysis Period (years)	Performance (years)	Mill Depth (in)	Overlay Thickness (in)	Present Worth ($)	Present Worth ($/lane mile)	Annuity ($/lane mile/year)
Rural Arterial/Collector 2-Lane (2-Way)	20	3.8	3	3	$761,640	$380,820	$26,754
Rural Arterial/Collector 4-Lane Divided & Rural Limited Access 4-Lane Divided	20	3.8	3	3	$1,631,067	$407,767	$28,648
Urban 4-Lane Arterial Divided (45 Mph)	20	3.8	3	3	$2,051,656	$512,914	$36,035
Urban 6-Lane Arterial Divided (<45Mph)	20	3.8	3	3	$2,565,651	$427,608	$30,042
Urban 5-Lane Arterial/Collector Undivided	20	3.8	3	3	$2,491,296	$498,259	$35,005

6.5.2. Mill and Inlay (4 inches)

The same procedure as previous section was undertaken for 4 inches of mill and inlay. The results for the analysis are in Table 6.7 and Table 6.8, representing the minimum and maximum probable life cycle costs, consecutively. The present worth was calculated with the FDOT custom LCCA software and was divided by the number of lanes to obtain the cost/lane mile. The annual worth was then calculated to obtain the annual worth per lane mile. This analysis is performed for six different road types. The annual worth ranged from $$21,102/lane mile to $33,284/lane mile.

Table 6.7: Mill and inlay (4 inches), discount rate 3.5% - maximum range

Road Type	Analysis Period (years)	Performance (years)	Mill Depth (in)	Overlay Thickness (in)	Present Worth ($)	Present Worth ($/lane mile)	Annuity ($/lane mile/year)
Rural Arterial/Collector 2-Lane (2-Way)	20	9.2	4	4	$600,715	$300,357	$21,102
Rural Arterial/Collector 4-Lane Divided & Rural Limited Access 4-Lane Divided	20	9.2	4	4	$1,241,919	$310,480	$21,813
Urban 4-Lane Arterial Divided (45 Mph)	20	9.2	4	4	$1,588,402	$397,100	$27,898
Urban 6-Lane Arterial Divided (<45Mph)	20	9.2	4	4	$2,197,413	$366,235	$25,730
Urban 5-Lane Arterial/Collector Undivided	20	9.2	4	4	$1,928,774	$385,755	$27,101

Table 6.8: Mill and inlay (4 inches), discount rate 3.5% - minimum range

Road Type	Analysis Period (years)	Performance (years)	Mill Depth (in)	Overlay Thickness (in)	Present Worth ($)	Present Worth ($/lane mile)	Annuity ($/lane mile/year)
Rural Arterial/Collector 2-Lane (2-Way)	20	6.2	4	4	$715,584	$357,792	$25,137
Rural Arterial/Collector 4-Lane Divided & Rural Limited Access 4-Lane Divided	20	6.2	4	4	$1,474,611	$368,653	$25,900
Urban 4-Lane Arterial Divided (45 Mph)	20	6.2	4	4	$1,895,064	$473,766	$33,284
Urban 6-Lane Arterial Divided (<45Mph)	20	6.2	4	4	$2,620,661	$436,777	$30,686
Urban 5-Lane Arterial/Collector Undivided	20	6.2	4	4	$2,301,152	$460,230	$32,333

6.5.3. Chip Seal

The construction cost to apply chip seal for three previous projects in Florida was $53,187/lane mile. Assuming a 12 foot lane width, the unit cost was $3.78/SY. This was used to calculate the present worth with the FDOT custom software. The thickness of the chip seal was assumed to be 3/8 inches. Milling depth used in the LCCA analysis was equal to the total thickness of pavement consisting of a friction course, AC overlay, and chip seal. The minimum and maximum results for this analysis are on Table 6.9 and Table 6.10. The results for chip seal exhibited the same trend for the annual worth/lane mile. The annual worth ranged from $21,867 /lane mile to $35,141 /lane mile/inch.

Table 6.9: Chip Seal, discount rate 3.5% - maximum range

Road Type	Analysis Period (years)	Performance (years)	Mill Depth (in)	Overlay Thickness (in)	Present Worth ($)	Present Worth ($/lane mile)	Annuity ($/lane mile/year)
Rural Arterial/Collector 2-Lane (2-Way)	20	5.8	3	2	$622,501	$311,251	$21,867
Rural Arterial/Collector 4-Lane Divided & Rural Limited Access 4-Lane Divided	20	5.8	3	2	$1,163,527	$290,882	$20,436
Urban 4-Lane Arterial Divided (45 Mph)	20	5.8	3	2	$1,670,208	$417,552	$29,335
Urban 6-Lane Arterial Divided (<45Mph)	20	5.8	3	2	$2,337,702	$389,617	$27,372
Urban 5-Lane Arterial/Collector Undivided	20	5.8	3	2	$1,715,082	$343,016	$24,099

Table 6.10: Chip Seal, discount rate 3.5% - minimum range

Road Type	Analysis Period (years)	Performance (years)	Mill Depth (in)	Overlay Thickness (in)	Present Worth ($)	Present Worth ($/lane mile)	Annuity ($/lane mile/year)
Rural Arterial/Collector 2-Lane (2-Way)	20	4.2	3	2	$748,306	$374,153	$26,286
Rural Arterial/Collector 4-Lane Divided & Rural Limited Access 4-Lane Divided	20	4.2	3	2	$1,417,117	$354,279	$24,890
Urban 4-Lane Arterial Divided (45 Mph)	20	4.2	3	2	$2,000,760	$500,190	$35,141
Urban 6-Lane Arterial Divided (<45Mph)	20	4.2	3	2	$2,801,706	$466,951	$32,806
Urban 5-Lane Arterial/Collector Undivided	20	4.2	3	2	$2,116,466	$423,293	$29,738

6.5.4. Hot-in-Place Recycling (HIPR)

Cost data of HIPR could be obtained based on actual HIPR projects in Florida. The typical thickness for HIPR is between 2 and 4 inches and its cost is about $7.00 per square yard. This value was used to calculate the LCCA with an overlying friction course as well. The analysis period was assumed to be 20 years. The results are presented in Table 6.11 and Table 6.12. The annual worth ranges from $17,638to $31,446/lane mile between the road types.

Table 6.11: HIPR, discount rate 3.5% - maximum range

Road Type	Analysis Period (years)	Performance (years)	Mill Depth (in)	Overlay Thickness (in)	Present Worth ($)	Present Worth ($/lane mile)	Annuity ($/lane mile/year)
Rural Arterial/Collector 2-Lane (2-Way)	20	9	---	2.5	$502,107	$251,054	$17,638
Rural Arterial/Collector 4-Lane Divided & Rural Limited Access 4-Lane Divided	20	9	---	2.5	$1,219,863	$304,966	$21,425
Urban 4-Lane Arterial Divided (45 Mph)	20	9	---	2.5	$1,571,586	$392,896	$27,603
Urban 6-Lane Arterial Divided (<45Mph)	20	9	---	2.5	$2,198,794	$366,466	$25,746
Urban 5-Lane Arterial/Collector Undivided	20	9	---	2.5	$1,908,354	$381,671	$26,814

Table 6.12: HIPR, discount rate 3.5% - minimum range

Road Type	Analysis Period (years)	Performance (years)	Mill Depth (in)	Overlay Thickness (in)	Present Worth ($)	Present Worth ($/lane mile)	Annuity ($/lane mile/year)
Rural Arterial/Collector 2-Lane (2-Way)	20	4.6	---	2.5	$698,827	$349,414	$24,548
Rural Arterial/Collector 4-Lane Divided & Rural Limited Access 4-Lane Divided	20	4.6	---	2.5	$1,226,869	$306,717	$21,548
Urban 4-Lane Arterial Divided (45 Mph)	20	4.6	---	2.5	$1,613,066	$403,266	$28,331
Urban 6-Lane Arterial Divided (<45Mph)	20	4.6	---	2.5	$2,576,188	$429,365	$30,165
Urban 5-Lane Arterial/Collector Undivided	20	4.6	---	2.5	$2,237,976	$447,595	$31,446

6.5.5. Cold-in-Place Recycling (CIPR)

According to the Missouri Department of Transportation, cold-in-place recycling cost about $41,045 - $46,147 per lane mile [70]. Therefore the average cost of cold-in-place recycling is considered to be $ 6.19/SY. The annual worth ranges from $20,379 - $30,872 /lane mile/year (

Table 6.13 and Table 6.14)

Table 6.13: CIPR, discount rate 3.5% - maximum range

Road Type	Analysis Period (years)	Performance (years)	Mill Depth (in)	Overlay Thickness (in)	Present Worth ($)	Present Worth ($/lane mile)	Annuity ($/lane mile/year)
Rural Arterial/Collector 2-Lane (2-Way)	20	8.8	---	2.5	$580,140	$290,070	$20,379
Rural Arterial/Collector 4-Lane Divided & Rural Limited Access 4-Lane Divided	20	8.8	---	2.5	$1,182,551	$295,638	$20,770
Urban 4-Lane Arterial Divided (45 Mph)	20	8.8	---	2.5	$1,533,317	$383,329	$26,931
Urban 6-Lane Arterial Divided (<45Mph)	20	8.8	---	2.5	$2,142,482	$357,080	$25,087
Urban 5-Lane Arterial/Collector Undivided	20	8.8	---	2.5	$1,861,885	$372,377	$26,161

Table 6.14: CIPR, discount rate 3.5% - minimum range

Road Type	Analysis Period (years)	Performance (years)	Mill Depth (in)	Overlay Thickness (in)	Present Worth ($)	Present Worth ($/lane mile)	Annuity ($/lane mile/year)
Rural Arterial/Collector 2-Lane (2-Way)	20	4.6	---	2.5	$662,255	$331,127	$23,263
Rural Arterial/Collector 4-Lane Divided & Rural Limited Access 4-Lane Divided	20	4.6	---	2.5	$1,350,845	$337,711	$23,726
Urban 4-Lane Arterial Divided (45 Mph)	20	4.6	---	2.5	$1,757,704	$439,426	$30,872
Urban 6-Lane Arterial Divided (<45Mph)	20	4.6	---	2.5	$2,454,281	$409,047	$28,738
Urban 5-Lane Arterial/Collector Undivided	20	4.6	---	2.5	$2,134,355	$426,871	$29,990

6.5.6. Asphalt rubber membrane interlayer (ARMI)

The current practice of the FDOT to mitigate reflective cracking is to use an ARMI. The same analysis procedure used above was used to calculate the LCCA for an ARMI. The results of this assessment are shown in Table 6.15 and Table 6.16. The pavement layers for this ARMI method consist of a 0.5 inch of ARMI, a friction course and a layer of HMA that changes accordingly with the milling depth. A 1.5-in. minimum lift of HMA is required over ARMI. The weighted average cost from 2012 was used for an ARMI. This cost was $5.30 per square yard and was obtained from FDOT's Specifications and Estimates website [69]. The annual worth ranges from $21,144- $35,587/lane mile.

Table 6.15: ARMI, discount rate 3.5% - maximum range

Road Type	Analysis Period (years)	Performance (years)	Mill Depth (in)	Overlay Thickness (in)	Present Worth ($)	Present Worth ($/lane mile)	Annuity ($/lane mile/year)
Rural Arterial/Collector 2-Lane (2-Way)	20	10	3	2	$601,936	$300,968	$21,144
Rural Arterial/Collector 4-Lane Divided & Rural Limited Access 4-Lane Divided	20	10	3	2	$1,213,931	$303,483	$21,321
Urban 4-Lane Arterial Divided (45 Mph)	20	10	3	2	$1,476,205	$369,051	$25,928
Urban 6-Lane Arterial Divided (<45Mph)	20	10	3	2	$2,601,451	$433,575	$30,461
Urban 5-Lane Arterial/Collector Undivided	20	10	3	2	$1,933,806	$386,761	$27,172

Table 6.16: ARMI, discount rate 3.5% - minimum range

Road Type	Analysis Period (years)	Performance (years)	Mill Depth (in)	Overlay Thickness (in)	Present Worth ($)	Present Worth ($/lane mile)	Annuity ($/lane mile/year)
Rural Arterial/Collector 2-Lane (2-Way)	20	4	3	2	$809,058	$404,529	$28,420
Rural Arterial/Collector 4-Lane Divided & Rural Limited Access 4-Lane Divided	20	4	3	2	$1,631,743	$407,936	$28,659
Urban 4-Lane Arterial Divided (45 Mph)	20	4	3	2	$2,026,175	$506,544	$35,587
Urban 6-Lane Arterial Divided (<45Mph)	20	4	3	2	$3,004,214	$500,702	$35,177
Urban 5-Lane Arterial/Collector Undivided	20	4	3	2	$2,495,366	$499,073	$35,062

6.5.7. Interlayer Stress-absorbing Composite (ISAC)

The cost of ISAC according to a technical report by the Illinois Department of Transportation ranges from $10 - $14 / linear foot [30]. The width of rolls of ISAC is 36 inches and the thickness is 0.15 inches per a brochure by Geoproducts, Inc. 2010. Therefore the price per square foot ranges from $3.33 to $4.60. The average of these two values is $3.95 / square foot which was used to calculate the LCCA for ISAC. The same procedure that was used to calculate ARMI was used to calculate ISAC as an overlay with an interlayer. The following tables show the minimum and maximum life cycle costs happening during a 20 year life cycle of maintaining a roadway. The annual worth ranges from $18,214 - $25,626/lane mile (Table 6.17 and Table 6.18).

Table 6.17: ISAC, discount rate 3.5% - maximum range

Road Type	Analysis Period (years)	Performance (years)	Mill Depth (in)	Overlay Thickness (in)	Present Worth ($)	Present Worth ($/lane mile)	Annuity ($/lane mile/year)
Rural Arterial/Collector 2-Lane (2-Way)	20	6.4	4.5	2	$518,501	$259,251	$18,214
Rural Arterial/Collector 4-Lane Divided & Rural Limited Access 4-Lane Divided	20	6.4	4.5	2	$860,362	$215,090	$15,111
Urban 4-Lane Arterial Divided (45 Mph)	20	6.4	4.5	2	$1,341,613	$335,403	$23,564
Urban 6-Lane Arterial Divided (<45Mph)	20	6.4	4.5	2	$1,991,035	$331,839	$23,313
Urban 5-Lane Arterial/Collector Undivided	20	6.4	4.5	2	$1,733,444	$346,689	$24,357

Table 6.18: ISAC, discount rate 3.5% - minimum range

Road Type	Analysis Period (years)	Performance (years)	Mill Depth (in)	Overlay Thickness (in)	Present Worth ($)	Present Worth ($/lane mile)	Annuity ($/lane mile/year)
Rural Arterial/Collector 2-Lane (2-Way)	20	5.4	3	2	$571,609	$285,805	$20,079
Rural Arterial/Collector 4-Lane Divided & Rural Limited Access 4-Lane Divided	20	5.4	3	2	$969,997	$242,499	$17,037
Urban 4-Lane Arterial Divided (45 Mph)	20	5.4	3	2	$1,482,492	$370,623	$26,038
Urban 6-Lane Arterial Divided (<45Mph)	20	5.4	3	2	$2,188,528	$364,755	$25,626
Urban 5-Lane Arterial/Collector Undivided	20	5.4	3	2	$1,904,511	$380,902	$26,760

6.5.8. Geotextile (Fabric)

Two contractors bid on a geotextile project for Louisiana DOT in 2006 (LA DOTD 2006). The contractors bid $10.00/SY and $3/SY, and the average of those bids, $6.50/SY, was used to calculate the use of fabrics as an interlayer. The same procedure for the LCCA with an ARMI was followed. The annual worth ranges from $5,964 - $15,263/lane mile/inch (Table 6.19 and Table 6.20).

Table 6.19: Fabrics, discount rate 3.5% - maximum range

Road Type	Analysis Period (years)	Performance (years)	Mill Depth (in)	Overlay Thickness (in)	Present Worth ($)	Present Worth ($/lane mile)	Annuity ($/lane mile/year)
Rural Arterial/Collector 2-Lane (2-Way)	20	8.8	3	2	$400,302	$200,151	$14,062
Rural Arterial/Collector 4-Lane Divided & Rural Limited Access 4-Lane Divided	20	8.8	3	2	$807,760	$201,940	$14,187
Urban 4-Lane Arterial Divided (45 Mph)	20	8.8	3	2	$1,099,702	$274,926	$19,315

Table 6.20: Fabrics, discount rate 3.5% - minimum range

Road Type	Analysis Period (years)	Performance (years)	Mill Depth (in)	Overlay Thickness (in)	Present Worth ($)	Present Worth ($/lane mile)	Annuity ($/lane mile/year)
Rural Arterial/Collector 2-Lane (2-Way)	20	7.6	3	2	$579,532	$289,766	$20,357
Rural Arterial/Collector 4-Lane Divided & Rural Limited Access 4-Lane Divided	20	7.6	3	2	$1,169,500	$292,375	$20,541
Urban 4-Lane Arterial Divided (45 Mph)	20	7.6	3	2	$1,547,309	$386,827	$27,176
Urban 6-Lane Arterial Divided (<45Mph)	20	7.6	3	2	$2,167,156	$361,193	$25,376
Urban 5-Lane Arterial/Collector Undivided	20	7.6	3	2	$1,878,876	$375,775	$26,400

6.5.9. Strata ®

There is not a considerable amount of resources about this technique. However, the average cost of implementing this methods is reported to be $5.80 /SY [71]. This amount is assumed as a basis to calculate the life cycle cost of Strata ®. The rest is the same as previous sections. The annual worth ranges from $21,499- $30,679/lane mile/inch (Table 6.21 and Table 6.22).

Table 6.21: Strata, discount rate 3.5% - maximum range

Road Type	Analysis Period (years)	Performance (years)	Mill Depth (in)	Overlay Thickness (in)	Present Worth ($)	Present Worth ($/lane mile)	Annuity ($/lane mile/year)
Rural Arterial/Collector 2-Lane (2-Way)	20	10.2	3	2	$612,039	$306,020	$21,499
Rural Arterial/Collector 4-Lane Divided & Rural Limited Access 4-Lane Divided	20	10.2	3	2	$1,201,711	$300,428	$21,106
Urban 4-Lane Arterial Divided (45 Mph)	20	10.2	3	2	$1,614,903	$403,726	$28,364
Urban 6-Lane Arterial Divided (<45Mph)	20	10.2	3	2	$2,265,550	$377,592	$26,528
Urban 5-Lane Arterial/Collector Undivided	20	10.2	3	2	$1,960,953	$392,191	$27,553

Table 6.22: Strata, discount rate 3.5% - minimum range

Road Type	Analysis Period (years)	Performance (years)	Mill Depth (in)	Overlay Thickness (in)	Present Worth ($)	Present Worth ($/lane mile)	Annuity ($/lane mile/year)
Rural Arterial/Collector 2-Lane (2-Way)	20	7.2	3	2	$678,283	$339,141	$23,826
Rural Arterial/Collector 4-Lane Divided & Rural Limited Access 4-Lane Divided	20	7.2	3	2	$1,307,992	$326,998	$22,973
Urban 4-Lane Arterial Divided (45 Mph)	20	7.2	3	2	$1,798,106	$449,526	$31,581
Urban 6-Lane Arterial Divided (<45Mph)	20	7.2	3	2	$2,520,914	$420,152	$29,518
Urban 5-Lane Arterial/Collector Undivided	20	7.2	3	2	$2,183,414	$436,683	$30,679

Figures 6.1 through 6.5 represent the graphs of the annual worth for different mitigation me thod. Each graph indicates the life cycle cost for a different road type. These graphs represe nt the average value of cost along with the floating bars that indicate the minimum and ma ximum values. As described in Chapter 5, the field performance of RC mitigation methods has shown variation; thus, a range of performance was used as inputs for the LCCA.

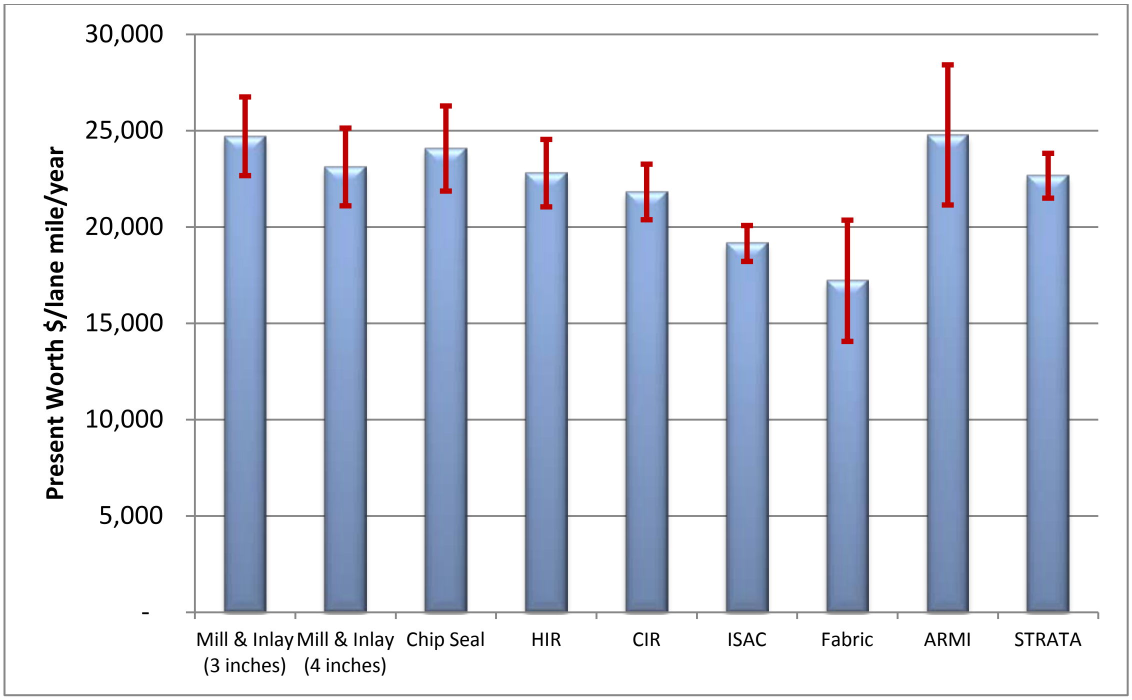


Figure 6.1: Present worth $/lane mile/year for rural arterial/collector 2-lane (2-way)

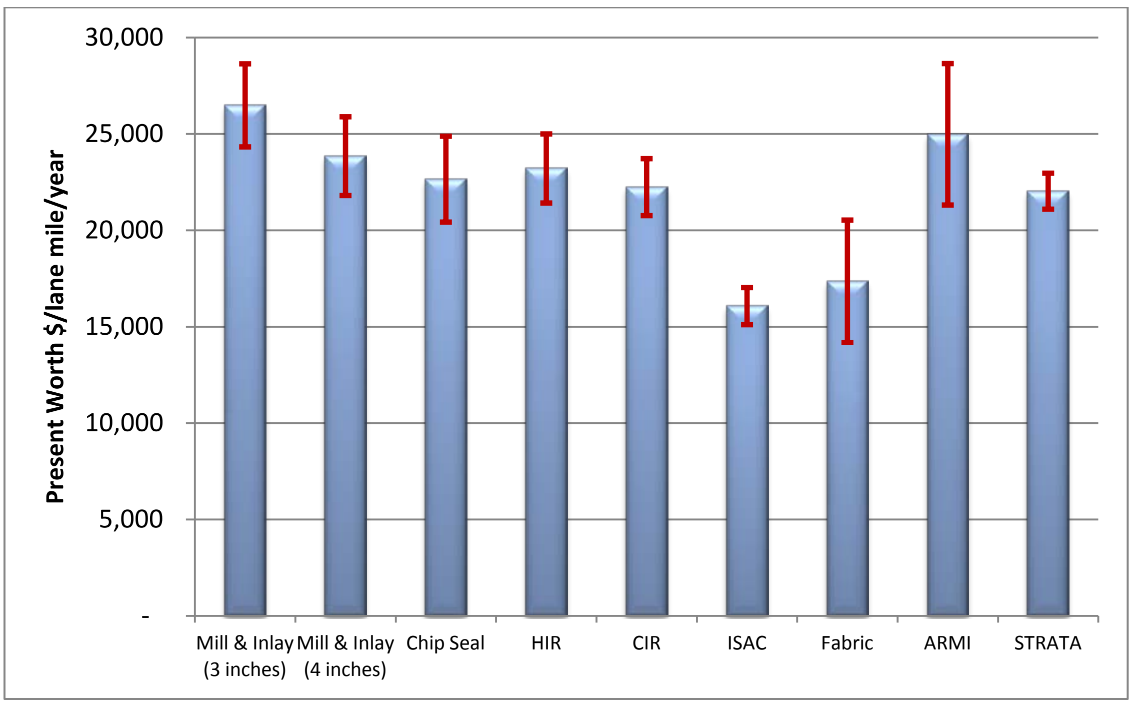


Figure 6.2: Present worth $/lane mile/year for rural arterial/collector 4-lane divided & rural limited access 4-lane divided

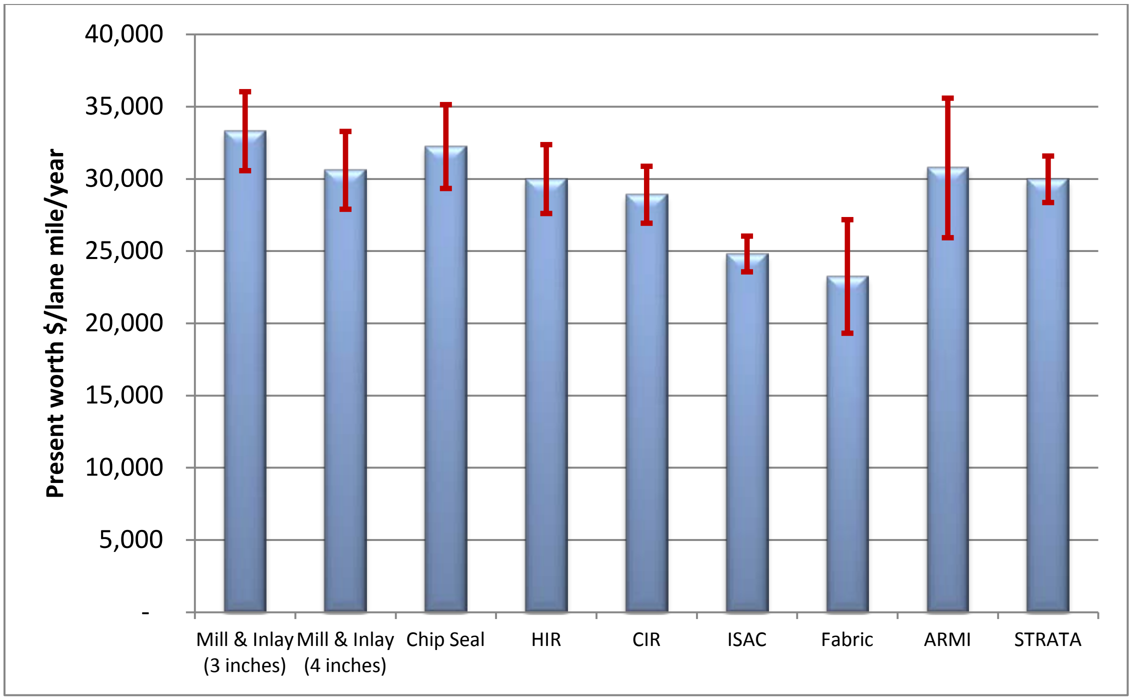


Figure 6.3: Present worth $/lane mile/year for urban 4-lane arterial divided (45 mph)

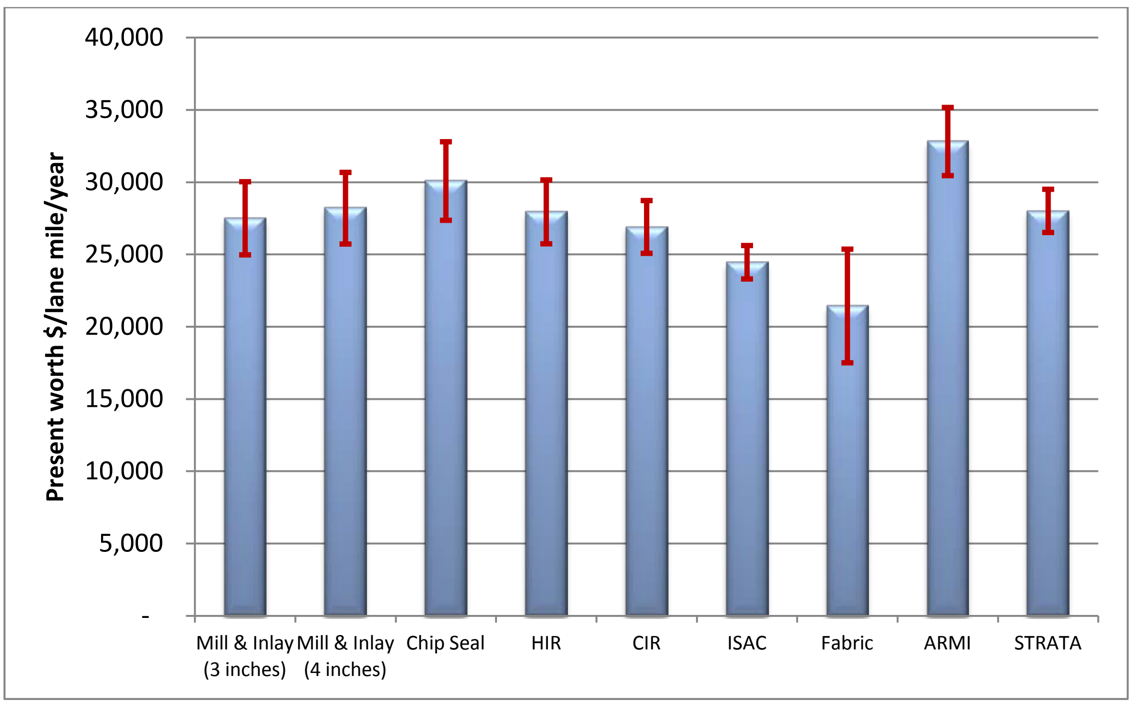


Figure 6.4: Present worth $/lane mile/year for urban 4-lane arterial divided (<45 mph)

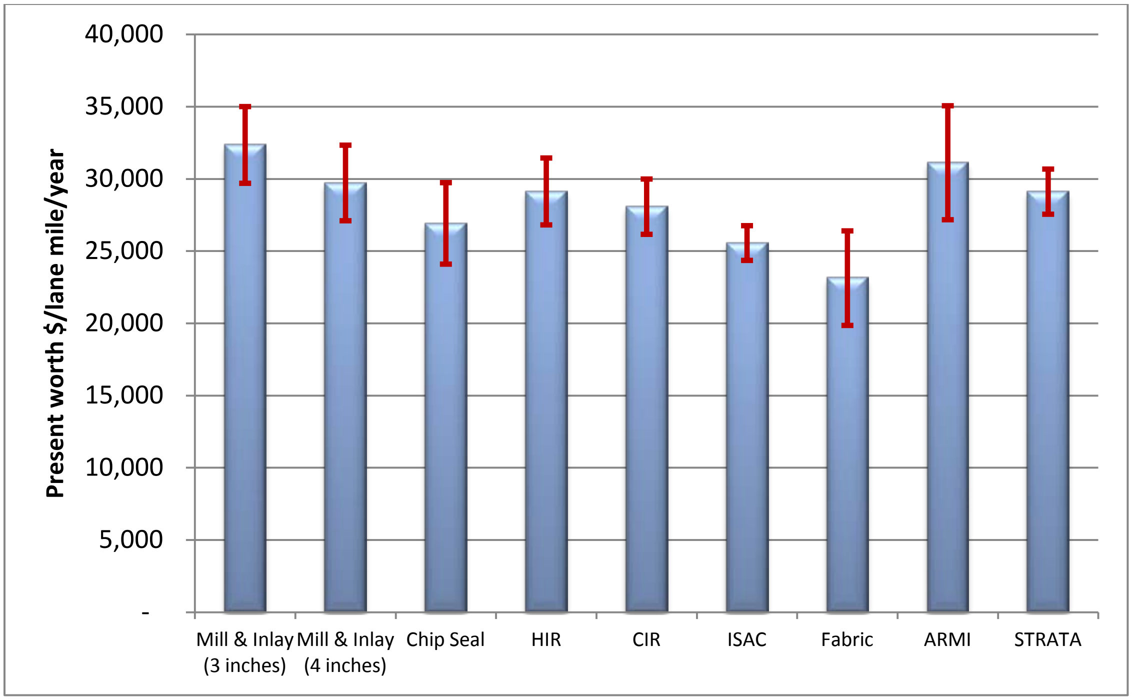


Figure 6.5: Present worth $/lane mile/year for urban 5-lane arterial/collector undivided

6.6. Summary and Conclusion

The LCCA results are summarized in Table 6.23 by showing the minimum and maximum annual worth of all of mitigation methods in $/lane mile. The annual worth represents maintenance annuity per year; thus lower values represent better cost-effective methods. As discussed, the life cycle is considered to be 20 years and similar costs between alternatives are not taken into account, as the main purpose of this LCCA is to compare the cost effectiveness not to determine the exact life cycle cost values. According the LCCA results, fabrics and ISAC have lower life cycle costs compared to other methods by showing lower annual worth values than other methods. On the other hand, the annual worth for the ARMI and mill and inlay are higher than the other methods. The ARMI and mill and inlay (3 inches) have the highest maintenance annuities among the proposed alternatives, with more than $35,000 per lane-mile maintenance costs for each year, in their maximum state.

Table 6.23: Annual worth of the RC mitigation methods ($/lane mile)

Road Type	M&I (3 inches)		M&I (4 inches)		Chip Seal		HIR		CIPR		ARMI		ISAC		`Fabric		STRATA	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Rural Arterial/ Collector 2-Lane (2-Way)	22,669	26,754	21,867	26,286	20,053	24,548	17,638	24,548	20,379	23,263	14,062	20,357	21,144	28,420	21,102	25,137	21,499	23,826
Rural Arterial/ Collector 4-Lane Divided & Rural Limited Access 4-Lane Divided	24,338	28,648	20,436	24,890	16,945	21,548	21,425	21,548	20,770	23,726	14,187	20,541	21,321	28,659	21,813	25,900	21,106	22,973
Urban 4-Lane Arterial Divided (45 Mph)	30,568	36,035	29,335	35,141	22,215	28,331	27,603	28,331	26,931	30,872	19,315	27,176	25,928	35,587	27,898	33,284	28,364	31,581
Urban 6-Lane Arterial Divided (<45Mph)	24,979	30,042	27,372	32,806	24,495	30,165	25,746	30,165	25,087	28,738	17,514	25,376	30,461	35,177	25,730	30,686	26,528	29,518
Urban 5-Lane Arterial/Collector Undivided	29,694	35,005	24,099	29,738	25,504	31,446	26,814	31,446	26,161	29,990	19,855	26,400	27,172	35,062	27,101	32,333	27,553	30,679

7. IDENTIFY TOP MITIGATION TECHNIQUE

7.1. Introduction

In this chapter, top RC mitigation methods have been identified, considering Florida's conditions. When an engineer selects the most effective RC mitigation method, many variables should be taken into account, such as factors include cost, performance, recyclability, design and construction familiarity, proprietary product, etc. A MCDM method was developed to take into account those variables as input parameters. Depending on the knowledge and experiences of the pavement engineer, those input variables may be weighted differently. Several scenarios with different weight factors of each variable have been investigated in the MCDM. A detailed description of the MCDM analysis and its results are presented in this chapter.

7.2. Multi-Criteria Decision Making Approach

To rank the reflective cracking mitigation methods, the MCDM approach was used to select the optimal mitigation method based on various criteria. This tool is widely used in situations where multiple conflicting criteria need to be evaluated in a decision making procedure. In these cases, a unique solution does not exist, and the preferences of decision makers play a vital role in finding the optimal solution. The general steps in conducting a MCDM method are as follows:

Step 1 – Determining the alternatives
Step 2 – Determining the criteria
Step 3 – Defining the weight of each criterion
Step 4 – Ranking each alternative based on different criteria
Step 5 – Running the MCDM tool and finding the top mitigation techniques

In this project, the MCDM tool customized for Florida's roads was developed. First of all, the possible mitigation techniques were selected based on previous research efforts through literature review, interviews, surveys, and numerical simulations. The outlined alternatives are as follows:

- Geotextile (Fabric)
- ISAC
- Chip seal
- Strata
- Cold-in-place Recycling (CIPR)
- Mill and Inlay (3 in)
- Mill and Inlay (4 in)
- ARMI

- Hot In Place Recycling (HIPR)

All interlayer methods are overlaid with an HMA overlay. Moreover, for the next step, the probable criteria as input variables for the MCDM are finalized based on expert's opinion. The selected criteria, which are key design considerations for selecting top RC mitigation methods, are shown below.

- Life cycle cost (LCC)
- Performance
- Recyclability
- Design and construction familiarity
- Proprietary product

These criteria were selected based on discussions with the UCF research group, FDOT's expert group as well as industry experts. After determining the most prominent criteria, each of these criteria was weighted based on the experts opinion. This is where the opinion of decision maker takes effect on the final decision. Life cycle cost represents the calculated LCCA values in the previous section. The ranking of each method based on its life cycle cost can be found from the calculated life cycle cost (see Chapter 6).

This tool enables the user to pick among the six different road types show in Table 6.23 and see the differences in life cycle cost. Performance criterion also follows the same concept that is explained in the performance section of Chapter 5. For recyclability, mitigation techniques are divided into two categories, recyclable and non-recyclable. The ranking of design and construction familiarity for each method is obtained from FDOT expert's opinion. Familiarity is ranked in a scale of 1 to 5, where 1 represents the lowest familiarity and 5 represents the highest familiarity. The proprietary ranking is determined based on whether the mitigation technique needs certain material or design procedure that is owned exclusively by one manufacturer or a single company. It is scaled in a range of 1 to 3, in which 1 means lowest proprietary and 3 means highest non-proprietary. Score 2 represents some extent of proprietary products and geotextile (or fabric) falls into this group. For example, new fabric products are being developed and introduced as proprietary product.

The MCDM spreadsheet then used an Analytical Hierarchy Process (AHP) to find the best mitigation method. The AHP is a multi-criteria decision making tool which was proposed by Saaty [72]. It is based on a pairwise comparison between alternatives and depends on a decision maker's judgment to select the best option. This method is typically used when the decision relies on the evaluation of alternatives in terms of criteria [73]. In this approach the decision-maker defines the value of one single comparison at a time. In this tool, the comparison is performed between the alternatives, which are the mitigation methods, and the above mentioned criteria. Each pairwise comparison requires the decision maker to provide an answer to the question: “Attribute A is how much more important than Attribute B, relative to the overall objective?”

To explain the mathematical content of the AHP method, consider there are M alternatives and N criteria. The performance matrix or the matrix of coefficient can be formed as shown in Figure 7.1.

	criterion			
	C1	C2	....	Cn
Alt.	W1	W2	....	Wn
A1	a11	a12	....	a1n
A2	a21	a22	....	a2n
......	......	......	......	......
Am	am1	am2	....	amn

Figure 7.1: Decision matrix

For each criterion, a specific weight is assigned and shown as W_i:

$$\sum_{1}^{n} w_i = 1$$

$$w_i \geq 0$$

So the final score of an alternative in an AHP method can be calculated as:

$$AHP_i = \sum_{j=1}^{n} a_{ij} w_j$$

$$for\ i = 1,2, \dots m$$

The MCDM spreadsheet is designed in a way that a decision maker can change the weights of each criterion and observe the changes in final score as well as the selected optimal mitigation method. Figure 7.2 shows the general framework of the MCDM Method.

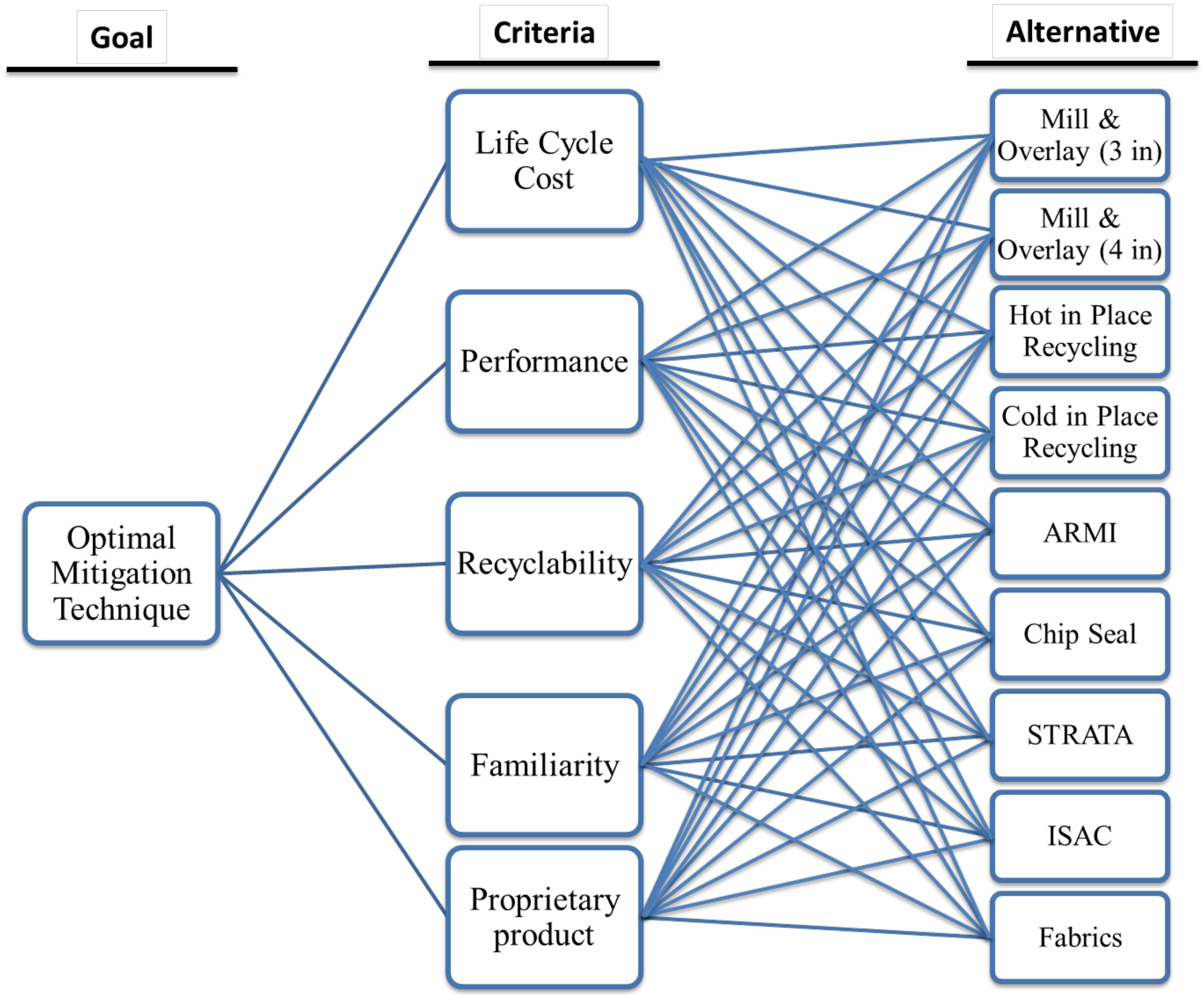


Figure 7.2: General framework of a MCDM model

The MCDM is an Excel based-Macro worksheet that enables the user to input his opinion about the weights of different criteria in the specified cells. In the multi-criteria decision making analysis, changing the weights of criteria has considerable effects on the final selection. To better understand the effect of weights in the final results, a strategic analysis was performed on the MCDM model using our assumed ranks for different methods.

7.3. Results of MCDM with Different Scenarios

As discussed, experiences and knowledge accumulated in the Districts can be reflected in deciding the weight factors of those multiple variables; thus the MCDM analyses with different scenarios are meaningful. The ultimate goal of this MCDM tool is to allow the users to input their expertise and opinions into the analysis process, which will better reflect conditions of specific projects. In this report, simulations of two scenarios are presented: (1) a strategy with budgetary limits and (2) a strategy based on performance. The budgetary-limit and performance-based cases consider the cost and performance as a primary input, respectively. Other combinations can be created by using the MCDM tool by the users.

7.3.1. Strategy with Budgetary Limits

A prominent criterion in highway construction projects is the project budget. In decision making, the life cycle cost is one of the most important considerations. In addition, a decision maker wants the construction to be completed as early as possible in order to minimize the overhead costs. In this regard, a decision maker can think of the scenario shown in Figure 7.1 for the weights of criteria. The sum of each weight of criteria will be one. The MCDM result of this scenario is presented in Table 7.2 showing the final score for this combination of weights. Higher scores in the MCDM results indicate a more effective method for the RC mitigation. In the scenario of the budgetary limit, fabric exhibited the highest score among other methods and can be selected as the best option. Mill and inlay (4-in. thickness) and ARMI are 2nd and 3rd places, respectively. The results show that chip seal and Strata options are two least effective methods. A typical pavement rehabilitation treatment includes a mill and inlay/overlay with 2 inches, which can be considered as a control section. The mill depth would be dependent on the existing conditions of pavements. The analysis illustrates that even 1-in. increase of the thickness (3-in. mill and inlay) results in comparable effectiveness.

Table 7.1: Weights of criteria for the strategy with budgetary limits

Criteria	**Weight**
LCC	0.5
Performance	0.2
Recyclability	0
Design and construction Familiarity	0.2
proprietary product	0.1

Table 7.2: Final score of the RC mitigation methods for the strategy with budgetary limits

Mitigation Technique	Final Score	Range of Performance (year)
Geosynthetic (Fabric)	0.93	3.8 – 4.9
Mill and Inlay (4 in)	0.91	3.1 – 4.6
Mill and Inlay (3 in)	0.85	1.9 – 2.6
ARMI	0.83	2.0 – 5.0
Cold-in-place Recycling	0.76	2.3 – 4.4
Hot In Place Recycling	0.74	2.3 – 4.5
ISAC	0.74	2.7 – 3.2
Strata	0.71	3.6 – 5.1
Chip seal	0.67	2.1 – 2.9

7.3.2. Strategy with Performance Priority

In this strategy, a decision maker considers the performance (or life span) of the selected method as top priority. The pavement performance here can be defined as a combination of structural and functional performance in the field. In other words, decision makers are willing to spend more on the best performing RC mitigation method. Table 7.3 shows the assigned weights in this case. As indicated in Table 7.4, the score of “Mill and Inlay (4 inches)” is higher than others, and the ARMI and fabric follows in the order. However, it is an important note that decision makers also need to carefully review the range of performance of each mitigation method along with the MCDM result for the final decision because uncertainty can be another factor affecting the decision making.

Table 7.3: Weights of criteria for the strategy with performance priority

Criteria	Weight
LCC	0.2
Performance	0.5
Recyclability	0.1
Familiarity	0.1
proprietary product	0.1

Table 7.4: Final score of the RC mitigation methods for the strategy with performance priority

Mitigation Technique	Final Score	Range of Performance (yr)
Mill and Inlay (4 in)	1.43	3.1 – 4.6
ARMI	1.37	2.0 – 5.0
Geosynthetic (Fabric)	1.36	3.8 – 4.9
Strata	1.34	3.6 – 5.1
Cold-in-place Recycling	1.29	2.3 – 4.4
Hot In Place Recycling	1.29	2.3 – 4.5
Mill and Inlay (3 in)	1.26	1.9 – 2.6
Chip seal	1.18	2.1 – 2.9
ISAC	1.15	2.7 – 3.2

7.4. A Design Guideline for Additional Overlay Thickness to Mitigate Reflective Cracking

The MCDM analysis concluded that an increase of inlay/overlay thickness would be the most effective RC mitigation method for the AC overlays over HMAs. Key design variables to be considered in the overlay design have been identified. The design variables are overlay thickness, existing pavement condition (including subsurface condition), design life, and traffic level. Important notes for each design variable are discussed as below.

1) **Overlay thickness:** Increasing the overlay thickness has two major benefits: 1) to reduce the level of stress/strain concentration at the crack tip and 2) to delay the onset of RC because of the increased overlay thickness. Due to the combination, doubling the overlay thickness generally more than doubles the pavement life; for example, a pavement where reflective cracking typically appears after 3 years may last until 6 years before reflective cracking is observed. A study in Texas [20] demonstrated that an overlay thickness two times thicker than structurally required one increased the time by three times until 50 % RC was observed. FEM analyses indicated that increasing the overlay thickness of 2 to 4 inches by an additional 1 inch reduced the tensile strain at the bottom of the overlay by approximately 30%. Reduction in tensile strain was almost zero after 5 inches (see Figure 4.16), which can be considered as the upper limit of an overlay thickness for the RC mitigation. It is important to note that a mill depth greater than 5 inches may not be practical [68].

2) **Design life (or Performance goal):** The design life of the inlay/overlay will affect the final thickness. Longer design lives result in thicker overlay requirements. The crack propagation rate of 1 inch per year [1, 6] (commonly accepted across the country) has been adopted as a method to determine the expected life associated with the RC (referred as the expected RC life). In the state of Florida, the warm climate will help delay the onset of RC, resulting in longer expected RC life compared with other states. The RC propagation rate may be less than 1 inch per year; however, the researchers recommend the 1 inch per year from a conservative viewpoint. A future study that better quantify the RC propagation rate of Florida's road systems will be necessary.

3) **Existing pavement condition:** Both surface distresses and subsurface conditions affect the performance of overlays. The extent, depth, and severity of cracking and other existing distresses (e.g. rutting) in asphalt pavements should be evaluated in order to select proper pre-overlay treatments as well as optimum thickness of an overlay. These surface distresses are addressed by the current rehabilitation design manual; for example, if extensive cracking is found, increasing the mill depth is warranted. However, a detailed crack map prior to the overlay will be necessary to evaluate and monitor the effect of RC on the long-term performance of pavements. In addition to the cracking map, the evaluation of load-transfer conditions at cracks (after milling) would be beneficial in selecting a proper rehabilitation strategy. TxDOT has extensively used a continuous deflection testing device, the Rolling Dynamic Deflectometer (RDD), for the selection of best pre-overlay treatments [22]. The RDD is capable of quantifying the load-transfer condition at cracks/joints in the existing pavements.

   The influence of the poor load-bearing condition from subsurface layers (base, subbase, and subgrade layers) can be added as one of inputs in determining the overlay thickness. Blankenship et al. [25] addressed that a poor base (or subbase) layer results in higher likelihood of reflective cracking. It was reported that pavements with strong bases exhibited a cracking rate of 13.0% per year, while pavements with weak bases showed 17.6% RC per year. The current FDOT overlay design utilizes the "structural number (SN)" approach, which indirectly represents the load-bearing capacity of subsurface layers. However, this overlay design does not reflect the RC mitigation in the final thickness calculated. To date, a clear relationship between reflective cracking and the condition of subsurface layers has not been developed. Developing the relationship between reflective cracking and the structural capacity of subsurface layers will enable design engineers to figure out how to utilize the existing SN in determining the overlay thickness associated with reflective cracking. A future research is recommended.

4) **Traffic level:** Traffic volume is also one of the key factors affecting the performance of overlays. In the current FDOT overlay design, traffic level information is used to determine the binder grade and the overlay thickness based on a traditional fatigue viewpoint. According to the RC mechanisms identified, a vehicle wheel load causes bending stress (predominant movement mode) as well as differential movements. Although the RC propagation rate of 1 inch per year is commonly used, the propagation

rate will vary depending on the traffic level, overlay fracture properties, and other factors previously described.. Thus, the correlation between the RC propagation rate and traffic level for the roads in Florida is recommended as future research.

There are several studies showing how to determine the thickness of a mill and inlay/overlay for typical pavement rehabilitation projects [78, 79, 81, 82]. However, these methods presented in the form of decision trees do not take into account for the issue of reflective cracking in the overlay designs. A design guideline of the additional overlay thickness associated with the RC mitigation has been drafted and presented as below.

The design guideline provides (1) calculation of the expected RC life of an overlay and (2) minimum and maximum thickness of the overlay to be placed for the RC mitigation.

An equation to calculate the expected RC life is shown below.

$$Y = X + 0.3 \cdot (X - 2)$$

Where Y = the expected RC life of an overlay; X = the total overlay thickness (in the range of 2 to 6 inches).

This equation accounts for (1) the RC propagation rate of 1 inch per year and (2) the percent reduction of tensile strain at the bottom of the overlay as the overlay thickness increases. The FEM analyses indicate that increasing the overlay thickness by 1 inch result in approximately 30 % reduction in tensile strain at the crack tip. As an example, if the current overlay design recommends the 3 inches of an overlay, the expected RC life would be 3 years; however, increasing the overlay from 3 inches to 5 inches (additional overlay thickness of 2 inches) may increase the total expected RC life by 5.9 years.

The minimum overlay thickness of 2 inches is recommended. Data and experience suggest that a minimum overlay thickness of 2 inches is used with or without interface layer[28]. Overlays less than 1.5 inches thick cool rapidly; thus, compaction to the required density level would be difficult. A poorly compacted overlay may result in high permeability, and allow water infiltration, resulting in moisture-related distresses [17]. A thin overlay (less than 2 inches) may also cause high stresss/strain concentration at the crack tip and, thus, result in premature reflective cracks. Therefore, a minimum of 2 inches is commonly adopted by many state DOTs.

The maximum overlay thickness of 6 inches is recommended. The overlay thickness more than 6 inches may not be practical considering the currently recommended mill depth of 5 inches. In addition, the FEM analyses have shown that the stress/strain reduction would be minimal after 5 inches. The principal strains with 5 and 6 inches are almost same. However, many field studies have shown successful field performance with the overlays of 6 inches [24].

7.5. Construction Guideline

According to the studies and analyses conducted in previous chapters, it can be concluded that the most effective RC mitigation method may be the thickness increase of mill and inlay/overlay for flexible pavements. For the mill and inlay/overlay, the current FDOT Specification includes the details of construction guideline [80]. However, although the mill and inlay is ranked as the top reflective cracking mitigation method, it is worthy to note key construction features of other mitigation methods. In particular, paving fabric has been ranked within the top three methods, which can be still considered as alternative method to mitigate reflective cracking under specific environment; for example, the areas that require moisture barrier or drainage function or the urban areas where additional overlay thickness may not be possible. Therefore, key features during construction for the rest of the RC mitigation methods have been investigated and this information is presented in Appendix C as supplementary data.

7.6. Summary

The MCDM analysis was performed to identify the top RC mitigation method. The key variables considered in the analysis were life cycle cost (LCC), performance, recyclability, design and construction familiarity, and proprietary product. The MCDM results indicate that the increased thickness of mill and inlay/overlay is the most effective method especially when recyclability, proprietary product, and design and construction familiarity issues are more important.

A design guideline for additional overlay thickness to mitigate reflective cracking was developed based on two principles: (1) 1 inch per year as RD propagation rate and (2) about 30% reduction in tensile strain at the crack tip by 1-inch additional thickness. It is recommended that the minimum and maximum of the final overlay thickness are 2 and 6 inches, respectively. A construction guideline for this mill and inlay/overlay can be seen in the FDOT Standard Specifications for Road and Bridge Construction 2014. Other than the mill and overlay, fabric, ARMI, Strata are the next top three methods, which can be still used as an alternative under special environmental or road conditions. Key features during construction for the rest of the methods have been investigated and they are summarized in Appendix C.

8. SUMMARY AND CONCLUSION

8.1. Summary of Findings

The primary objective of this study was to identify the top RC mitigation methods considering Florida's road and climate conditions. The research methodology included a literature review, survey, personal interviews, data collection, numerical simulation, LCCA, and MCDM analyses. Theses research efforts were aimed at (1) investigating the current RC mitigation practice across the country, (2) understanding Florida's conditions as well as its pavement rehabilitation practice, (3) understanding the exact mechanism of RC in an AC overlay over HMA, (4) evaluating the cost benefit of RC mitigation methods, and finally (5) identifying the top RC mitigation method for Florida's road conditions. The summary of key findings is presented as below.

- Most previous studies have reported the same RC mechanisms for the overlay over HMA and the overlay over JCP. The predominant movement modes of the underlying layer determine the mode of RC mechanism in the overlays; thus, the underlying HMAs and JCPs will generate different movements under traffic and environmental loading. Under wheel loads, vertical differential movements at joints are predominant in JCPs while bending deformation will be major movement in HMAs. The fracture modes in the overlay will be different depending on the type of pavement either HMA or JCP.

- In Florida, an ARMI has been commonly used as the RC mitigation method. Some projects with an ARMI exhibited the service life from 8 to 13 years, which may be 2 to 5 years long than those without an ARMI. Some cases have shown good performance of an ARMI but mixed field performance has been reported throughout the state, which is a primary concern on the ARMI.

- In addition, rutting has been observed as a secondary issue. The rutting may be due to the material flexibility of an ARMI; thus, the minimum thickness of overlays will be important to assure low level of stress concentration on the ARMI layer. A comprehensive study on the poor performance of an ARMI has not been conducted. An ARMI can still be one of top RC mitigation methods if design, material, and construction improvements are made.

- According to the survey, a majority of SHAs do not have an overlay design method specifically for the RC mitigation purpose. Most SHAs select a RC mitigation method based on their experience from trial and error. The survey result shows that a majority of SHAs (40 % of the respondents) selected the increased thickness of overlay as the most promising method. In addition, different types of interlayer system are also used from state to state and their field performance varies.

- Different cracking conditions (e.g., full-depth, partial top-down and bottom-up cracks) in the underlying layer will create different conditions of stress and strain development at the tip of crack. The FEM analyses show that the top-down crack creates lowest tensile strain at the bottom of the overlay and the full-depth crack produces largest shear stress at the tip of crack. Among three cracking conditions, the top-down crack likely causes the least damage to the overlay, resulting in longer service life of the overlay.

- According to the FEM results, fabric can be effective in absorbing tensile and shear stress at the tip of crack; however, due to large deformation in the plane of fabric, crack development at the bottom of the overlay can be a concern under repeated traffic loads. The crack in the underlying layer may not propagate through the fabric but large horizontal deformation of the fabric can affect the performance of the AC overlay, especially crack development at the bottom of the overlay.

- Increased thickness of mill and inlay (or overlay) would be more effective in decreasing stress concentration and tensile-strain developed at the bottom of the overlay. The tensile strain at the tip of crack decreases proportionally as the overlay thickness increases. When the overlay thickness increases from 2 to 4 inches and from 3 to 4 inches, the principal strain decreases around 40 % and 25 %, respectively. On average, additional overlay thickness of 1 inch reduces 30% reduction in tensile strain.

- Among three mitigation methods, the FEM results indicated that the ARMI is an intermediate method from the perspective of stress and strain concentration, but low stiffness of ARMI layers can cause some deformation issues such as rutting.

- The LCCA is a part of the MCDM analysis as cost criterion. The LCCA alone indicates that fabric and ISAC are more cost effective than other methods when not considering constructability and other issues. The results show that the annual worth of fabric and ISAC is lower than other alternatives, which mean lower maintenance annuity per year. On the other hand, an ARMI and mill and inlay (3 inches) exhibited higher maintenance annuities than other methods. Increasing the thickness of mill and inlay decreases the annual worth but it is still not the best option from the LLCA perspective alone.

- The variables used in the MCDM analysis are life cycle cost, performance (or life span), recyclability, design and construction familiarity, and proprietary product. Depending on the weight of each criterion, multiple scenarios can be possible. For the budget-limited scenario (no consideration of the recyclability), fabric is the most effective methods followed by the mill and inlay (with 4 inches) and ARMI. On the other hand, the performance-priority scenario (considering the recyclability) resulted in the mill and inlay (with 4 inches) as the top effective method followed by an ARMI and fabric. The author’s interpretation is that fabric is cost effective and performs well but the recyclability reduces its effectiveness. On the other hand, increasing thickness of mill and inlay/overlay becomes more effective as recyclability get more important.

8.2. Conclusions and Recommendations

Based on the results of this study, conclusions and recommendations are made and summarized as below.

- The performance of currently available RC mitigation methods significantly vary. Also, the mixed field performance has been reported depending on data sources. Thus, the meaningful approach to rank those RC mitigation methods should be based on the performance comparison between the RC mitigation methods and control section especially under similar traffic and environmental conditions.

- Based on the results of the survey, FEM, and MCDM analyses, it is recommended that the top RC mitigation method considering Florida's road and climate conditions would be the increase of the thickness of mill and inlay (or overlay) (e.g., 4 inches or thicker).

- The next top two RC mitigation methods are fabric and ARMI, respectively. Therefore, some special environments may still require the use of fabric or ARMI as an alternative method. Fabric would be more appropriate than the mill and inlay for the following conditions: (1) when a budget-limited design with a low aspect of recycling is required; (2) in case the milling depth cannot be more than 4 inches by some other reasons (e.g., road and construction restrictions) in urban roads; and (3) when significant moisture damage or pumping are expected as major causes of pavement distresses.

- Traffic, temperature, and material aging would be the key factors affecting the performance of AC overlays. According to the survey by Bennert [23], in the state of Florida, time to observe the RC was reported as more than 4 years, which is longer than any other state in the U.S. Florida's warmer climate help to retard the RC; however, stiff binder and material aging along with traffic will be the major cause of RC. Thus, it is recommended to investigate the effect of binder and material aging in the RC performance.

- The two benefits of the increased overlay thickness are (1) longer time for RC to propagate through the overlay (based on 1 inch per year as the propagation rate) and (2) reduction of tensile strain at the bottom of overlay. A recommended method to estimate the expected RC life for a given overlay thickness is:

$$Y = X + 0.3\,(X - 2)$$

where *Y* = the expected RC life of an overlay; *X* = the total thickness of the overlay (in the range of 2 to 6 inches). The researchers recommend using a minimum of 2 inches and a maximum of 6 inches for the final thickness of overlays.

Recommended Future Studies:

- This study was based on "office works" such as literature review, survey, numerical analysis, and cost-benefit analysis; thus, the field implementation and long-term performance evaluation will be necessary. Although many of other field case studies were reviewed and analyzed through literatures, detailed information (e.g. ESAL, pavement layer thickness, mixture properties, climate, failure criteria, etc.) was often not available, thus accurate performance evaluation was limited. The recommendation is to conduct a pilot project by constructing in-service pavements with the identified top RC mitigation methods (e.g. mill and inlay, fabric, and ARMI) and monitoring the field performance over time. A detailed cracking map before the overlay placement will be required.

- The RC propagation rate is the most critical input for the overlay design with respect to reflective cracking. The propagation rate will be influenced by (1) traffic volume, (2) structural condition of existing pavement (e.g. SN_{eff}), and (3) material type (e.g. binder grade, RAP content, etc.). It is recommended to investigate the impact of those affecting variables on the RC propagation rate. Once the impacts are quantified, the proper RC propagation rates can be constructed. Subsequently, the RC propagation rate needs to be calibrated with the field performance data of in-service roads trafficked under Florida's climate.

REFERENCES

1. Hughes, J.J. and Al-Qadi, I.L., Evaluation of Steel Paving Mesh, FHWA Construction Report, Report No. FHWA-PA-2002-001, Harrisburg, PA, (2001)
2. Zhou, F., Hu, S., Hu, X., and Scullion, T., Mechanistic-Empirical Asphalt Overlay Thickness Design and Analysis System, FHWA/TX-09/0-5123-3 (2009)
3. Von Quintus, H.L., Mallela, J., Weiss, W., and Shen, S., Techniques For Mitigation Of Reflective Cracks, An AAPTP Research Report, (2009)
4. Symons, M. and Herrin, S., Techniques for Mitigation of Reflective Cracks, Technical Guide, AAPTP 05-04, 217, (2009)
5. Lytton, R.L., Tsai, F.L., Lee, S.-I., Luo, R., Hu, S., and Zhou, F., Models for Predicting Reflection Cracking of Hot-Mix Asphalt Overlays, NCHRP Report 669, (2010)
6. Thompson, M., Road Reflective Cracking System Under Cold Climatic Conditions, Evaluation and Study of the Fiber-Reinforced Emulsion Membrane, International Symposium on Asphalt Emulsion Technology (ISAET), (2008)
7. Ahlrich, R.C., Evaluation of Asphalt Rubber and Engineering Fabrics as Pavement Interlayers, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS, Miscellaneous Paper GL-86-34, (1986)
8. California Department of Transportation, *Flexible Pavement Rehabilitation Manual.* (2001)
9. Caltrans Maintenance Technical Advisory Guide (TAG), (2003)
10. Von Quintus, H.L., Mallela, J., and Lytton, R., Techniques for Mitigation of Reflective cracks, FAA Worldwide Airport Technology Transfer Conference, (2010)
11. Dempsey, B., *Development and Performance of Interlayer Stress-Absorbing Composite in Asphalt Concrete Overlays.* Transportation Research Record: Journal of the Transportation Research Board. 1809(-1): p. 175-183 (2002)
12. Dempsey, B.J. and Mukhtar, M.T., Interlayer Stress Absorbing Composite in AC Overlays, Aircraft/Pavement Technology In the Midst of Change, pp. 244-258, (1997)
13. Mukhtar, M.T., Interlayer Stress Absorbing Composite (ISAC) for Mitigating Reflection Cracking in Asphalt Concrete Overlays, Ph.D., University of Illinois at Urbana-Champaign, Urbana, IL., (1994)
14. Al-eis, K.A., Evaluation of the Interlayer Stress-Absorbing Composite (ISAC) to Mitigate Reflective Cracking in Asphaltic Concrete Overlays, WI-09-04. Wis DOT, (2004)
15. Greene, J., Kim, S., Chun, S., and Choubane, B., Effect of Asphalt Rubber Membrane Interlayer (ARMI) on Instability Rutting and Reflection Cracking of Asphalt Mixture, (2012)
16. Roque, R., Chen, Y., and Lopp, G., Final Report Evaluation of Asphalt Rubber Membrance Interlayer (Armi) Using the University of Florida's Composite System Interface Cracking (CSIC) Test FDOT report, (2012)
17. Button, J. and Lytton, R., Guidelines for Using Geosynthetics with HMA Overlays to Reduce Reflective Cracking, Report 1777-P2, (2003)
18. Loria, L., Sebaaly, P., and Hajj, E., *Long-Term Performance of Reflective Cracking Mitigation Techniques in Nevada.* Transportation Research Record: Journal of the Transportation Research Board. 2044(-1): p. 86-95 (2008)
19. Amini, F., Potential Applications of Paving Fabrics to Reduce Reflective Cracking,

Jackson State University,Prepared for Mississipi Department of Transportation, FHWA/MS-DOT-RD-05-174, (2005)

20. Way, G.B., *Flagstaff I-40 Asphalt Rubber Overlay Project Nine Years of Success.* Transportation Research Board. (1990)
21. Chowdhury, A., Button, J.W., and Lytton, R.L., Tests of HMA Overlays Using Geosynthetics to Reduce Reflection Cracking, FHWA/TX-10/0-1777-3, (2009)
22. Chen, D., Won, M., Scullion, T., and Bilyeu, J., Minimizing Reflective Cracking With Applications of the Rolling Dynamic Deflectometer and Overlay Tester, National Conference on Preservation, Repair, and Rehabilitation of Concrete Pavements, St. Louis Missouri, April 21-24, 2009, pp 3–14,
23. Baek, J., Al-Qadi, I., Xie, W., and Buttlar, W., *In Situ Assessment of Interlayer Systems to Abate Reflective Cracking in Hot-Mix Asphalt Overlays.* Transportation Research Record: Journal of the Transportation Research Board. 2084(-1): p. 104-113 (2008)
24. Carmichael Iii, R. and Marienfeld, M., *Synthesis and Literature Review of Nonwoven Paving Fabrics Performance in Overlays.* Transportation Research Record: Journal of the Transportation Research Board. 1687(-1): p. 112-124 (1999)
25. Blankenship, P., Iker, N., and Drbohlav, J., *Interlayer and Design Considerations to Retard Reflective Cracking.* Transportation Research Record: Journal of the Transportation Research Board. 1896(-1): p. 177-186 (2004)
26. Hajj, E.Y., Sebaaly, P.E., and Loria., L., Reflective Cracking of Flexible Pavements – Phase I and II Recommendations, Pavements/Materials Program, Department of Civil and Environmental Engineering, College of Engineering, University of Nevada, Reno, Nevada, (2008)
27. Haltz, R.D., Christopher, B.R., and Berg, R.R., Gesynthetic Design and Construction Guidelines, US Department of Transportation, p. 460, (1998)
28. Barksdale, R.D., Fabrics in Asphalt Overlays and Pavement Maintenance, National Cooperative Highway Research Program, National Research Council, Washington, D.C., (1991)
29. Buttlar, W.G., Bozkurt, D., and Dempsey, B.J., Evaluation of Reflective Crack Control Policy, Illinois Transportation Research Center, (1999)
30. Vespa, J.W., Materials, I.D.o.T.B.o., and Research, P., *An Evaluation of Interlayer Stress Absorbing Composite (ISAC) Reflective Crack Relief System: Final Report*. Illinois Department of Transportation, Bureau of Materials and Physical Research, (2005)
31. Elseifi, M. and Bandaru, R., Cost Effective Prevention of Reflective Cracking of Composite Pavement, FHWA/LA.11/478, (2011)
32. SemMaterials^{SM}, *Reflective Crack Mitigation Using an Asphalt Concrete Interlayer System*, in *Pavement Performance Prediction Symposium*. 2007.
33. Button, J.W., *Overlay Construction and Performance Using Geotextiles.* Transportation Research Board. No. 1248, pp. 24-33 (1989)
34. Bennert, T. and Maher, A., *Evaluation of Current State of Flexible Overlay Design for Rigid and Composite Pavements in the United States.* Transportation Research Record: Journal of the Transportation Research Board. 1991(-1): p. 97-108 (2007)
35. Timm, D.H. and Warren, A.M., Performance of Rubblized Pavement Sections in Alabama Highway Research Center, Auburn University, IR-04-02, (2004)
36. Bemanian, S. and Division, N.D.o.T.M., *Cost-effective Rehabilitation of Portland Cement Concrete Pavement in Nevada*. University of Nevada, Reno, (1997)

37. Maurer, D.A. and Malasheskie, G.J., *Field performance of fabrics and fibers to retard reflective cracking.* Geotextiles and Geomembranes. 8(3): p. 239-267 (1989)
38. Al-Qadi, I.L., Buttlar, W.G., Baek, J., and Kim, M., Cost-Effectiveness and Performance of Overlay Systems in Illinois - Volume 1: Effectiveness Assessment of HMA Overlay Interlayer Systems Used to Retard Reflective Cracking, Research Report ICT-09-044 (2009)
39. Tighe, S., Haas, R., and Ponniah, J., *Life-Cycle Cost Analysis of Mitigating Reflective Cracking.* Transportation Research Record: Journal of the Transportation Research Board. 1823(-1): p. 73-79 (2003)
40. De Bondt, A.H., Anti-Reflective Cracking Design of (Reinforced) Asphalt Overlays, Ph.D. Dissertation, Department of Civil Engineering, Delft University of Technology, Delft, The Netherlands, (1998)
41. Nesnas k and Nunn, M.E., A Model for Top-Down Reflection Cracking in Composite Pavements 5th International RILEM Conference, Limoges, France, (2004)
42. 268, N.R.R.D., *Performance of Pavement Subsurface Drainage.* Transportation Research Board, National Research Council, Washington, D.C (2002)
43. Kandhal, P.S., Lubold, C.W., and Roberts, F.L., *Water Damage to Asphalt Overlays: Case Histories.* Proceedings of the Association of Asphalt Paving Technologists, Vol. 58 (1989)
44. National Asphalt Pavement Association, *Moisture Susceptibility of HMA Mixes: Identification of Problem and Recommended Solutions.* Quality Improvement Publication 119. (1992)
45. Elseifi, M. and Al-Qadi, I., *Modeling of Strain Energy Absorbers for Rehabilitated Cracked Flexible Pavements.* Journal of Transportation Engineering. 131(9): p. 653-661 (2005)
46. Nesnas K and Nunn M E, Thermal Pavement Response Model for Top-Down Reflection Cracking in Composite Pavements, The Transportation Research Board 85th Annual Meeting, Washington, D.C., (2006)
47. Kim, J., Sholar, G.A., and L, H., Evaluation of Segregation for Top-Down Cracking and Rutting Performance and Detecting Low-Performance Segregated Mixtures, FL/DOT/SMO/06-500, (2006)
48. Myers, L.A. and Roque R, *Top-Down Crack Propagation in Bituminous Pavements and Implications for Pavement Management.* Journal of the Association of Asphalt Paving Technologists. Vol. 71, pp. 651-670 (2002)
49. Kim, J., Accurate Determination of Dissipated Creep Strain Energy and Its Effect on Load- and Temperature-Induced Cracking of Asphalt Pavement, Ph.D. Dissertation, University of Florida, Gainesville, Florida, (2005)
50. Nazef, A., US 27/SR 25 Pavement Evaluation, FL/DOT/SMO/11-542, (2011)
51. SAS, ANSYS 13 Finite Element Analysis System, SAS IP, Inc, (2013)
52. Koh, C.S., Tensile Properties of Open Graded Friction Course (ODFC) Mixture To Evaluate Top-Down Cracking Performance, Dissertation, University of Florida, (2009)
53. Strategic Highway Research Program, SHRP's Layer Moduli Back calculation Procedure, (1993)
54. Strategic Highway Research Program (SHRP), Stiffness of Asphalt-Aggregate Mixes, (1994)
55. Roque, R., Koh, C., Chen, Y., Sun, X., and Lopp, G., Introduction of Fracture Resistance to the Design and Evaluation of Open Graded Friction Courses in Florida, FDOT report,

(2009)
56. Al-Azzawi, A.A., *Fininte Element Analysis of Flexible Pavements Strengthed With Geogrid.* ARPN Journal of Engineering and Applied Sciences. (2012)
57. Baek, J., Modeling Reflective Cracking Development in Hot-Mix Asphalt Overlays and Quantification of Control Techniques, University of Illinois at Urbana-Champaign, (2010)
58. Kruntcheva, M., Collop, A., and Thom, N., *Effect of Bond Condition on Flexible Pavement Performance.* Journal of Transportation Engineering. 131(11): p. 880-888 (2005)
59. Chen, Y., Lopp, G., and Roque, R., *Effects of an Asphalt Rubber Membrane Interlayer on Pavement Reflective Cracking Performance.* Journal of Materials in Civil Engineering. 25(12): p. 1936-1940 (2013)
60. Xu, Q. and Solaimanian, M., *Measurement and Evaluation of Asphalt Concrete Thermal Expansion and Contraction.* Journal of Testing and Evaluation, Vol 36, No. 2, pp. 1-10. (2007)
61. Neville, A.M., Properties of Concrete, 5th edition, Pearson (publisher), (2011)
62. Predoehl, N.H., Evaluation of Paving Fabric Test Installations in California, California Department of Transportation, FHWA/CA/TL-90/02, (1990)
63. Asphalt Recycling and Reclaiming Assosiation (ARRA), Asphalt recycling manual, (2001)
64. Terrel, R.L. and Hicks, R.G., Viability of Hot In-Place Recycling as a Pavement Preservation Strategy California Pavement Preservation Center, CP2C- 2008 - 106 (2008)
65. FHWA, *Improving Transportation Investment Decisions Through Life-Cycle Cost Analysis.* (2013)
66. Walls, J. and Smith, M., Life-Cycle Cost Analysis in Pavement Design Interim Technical Bulletin, Federal Highway Association (1998)
67. Evans, M., Using Life Cycle Cost Analysis in Highway Project Development, Preliminary Investigation, Caltrans Division of Research and Innovation, (2011)
68. Florida Department Of Transportation, Flexible Pavement Design Manual, Pavement Management Office, Document No. 625-010-002-g, (2008)
69. Florida Department Of Transportation, Historical Cost and Other Information, http://www.dot.state.fl.us/specificationsoffice/Estimates/HistoricalCostInformation/HistoricalCost.shtm, (2013)
70. Missouri Department of Transportation, Organizational Results Division, Analysis of Cold In-place Recycled Asphalt Pavements, (2009)
71. Bandaru, R., Cost Effective Prevention Of Reflective Cracking In Composite Pavements, The Department of Civil and Environmental Engineering, Louisiana State University, (2010)
72. (!!! INVALID CITATION !!!)
73. Triantaphyllou, E. and Mann, S.H., Using the Analytic Hierarchy Process for Decision Making in Engineering Applications, Some Chalanges. International Journal of Industrial Engineering, 2(1), 35–44, (1995)
74. Hicks, R.G., Seeds, S.B., and Peshkin, D.G., Selecting a Preventive Maintenance Treatment for Flexible Pavements, Foundation for Pavement Preservation, (2000)
75. Tenison, J.H. and Hanson, D.I., Pre-Overlay Treatment of Existing Pavements, NCHRP Synthesis 388, TRB, Washington D.C., (2009)
76. Federal Highway Administration, Techniques for Pavement Rehabilitation, National

Highway Institute, Reference Manual (Sixth Edition), Course No.13108, Publication No. FHWA HI-98-033, Washington, DC, (1998)
77. Galehouse, L., *Innovative Concepts for Preventive Maintenance.* In Transportation Research Record 1627, Transportation Research Board. (1998)
78. Pennsylvania Department of Transportation, Bituminous and Cement Concrete Pavement Treatment Strategies, Material Quality, and Cost Calculations and Indices, Bureau of Maintenance and Operations, (1998)
79. National Cooperative Highway Research Program, Accelerated Field Test of Performance-Related Specifications for Hot-Mix Asphalt Construction, NCHRP Project No. 9-20 (in progress), Transportation Research Board, National Research Council, Washington, DC, (1998)
80. Florida Department Of Transportation, Standard Specifications for Road and Bridge Construction (2014)
81. New York State DOT, Pavement Rehabilitation Manual Volume II: Treatment Selection. NYDOT, Materials Bureau, (1993)
82. Monismith, C.L., Pavement Management: Proceedings of National Workshop, FHWATS-82-203, Federal Highway Administration, (1981)
83. McKeen, R.G. and Lytton, R.L., Development of a Generic Specification for Reinforcing Fabrics, New Mexico Engineering Research Institute, New Mexico State Highway Department, (1982)
84. Tencate Company, *Paving fabric interlayer guide specification.* (2011)
85. Tencate Company, Instalation guidelines for pavement overlays using TENCATE MIRAFI MPV Nonwovens, (2011)
86. Bischoff, D., Evaluation of Strata® Reflective Crack Relief System, FEP-01-07, Wis DOT, (2007)
87. http://www.dot.state.oh.us/districts/D03/Pages/ChipSealFactSheet.aspx.
88. Sholar, G.A., Musselman, J.A., Page, G.C., Upshaw, P.B., and Moseley, H.L., Evaluation of Two Hot-In-Place Recycling Projects, FL/DOT/SMO/02-455, (2002)

APPENDIX A

Appendix A presents a summary of survey results conducted by Carmichael and Marienfeld [24]

Table A.1: Survey for AC overlay with paving fabric on existing PCC pavements

Site Location	Opening Date	Time Years	Observations, Results and Comments	Reference Number
California	Sep 1975	11.0	The existing PCC pavement was highly fractured. The rehabilitation design was directed to impede reflection cracking, despite anticipated large magnitude deflections. The rehabilitation section consisted of a nominal 25.4 mm (1 in) leveling course, paving fabric and a nominal 50.8 mm (2 in) AC overlay. After eleven years the pavement was performing well with 10% reflection of the longitudinal joints and 20% reflection of transverse joints. The pavement was still smooth with no evidence of distress.	8
California	Oct 1975	11.0	The existing PCC pavement was constructed in 1975 and displayed a moderate amount of block cracking and local subsidence. The design consisted of placement of a paving fabric and installation of a 76.2 mm (3 in) AC overlay. The overlay survived unusually severe winter. After 11 years the pavement was performing well with10% reflection of longitudinal joints and 15% reflection of transverse joints.	8
Georgia	Mid 1976	6.0	For HMAC overlays of 50.8 mm (2 in) and 101.6 mm (4 in), control sections developed 60% reflection cracking within 0.5 and 2.5 years, respectively. The same overlays [i.e., 50.8 mm (2 in) and 101.6 mm (4 in) thicknesses] composed of fabric had 60% cracking within 2.5 and 5.5 years, respectively.	9
California	Jan 1977	10.0	There is little benefit of fabric for thick AC overlays [> 121.9 mm (0.4 ft)] of distressed PCC pavements, since most cracking is thermal in nature and fabric does not add any retardation ability to thicker overlays. An AC overlay, 0.40 feet or greater thickness is needed to retard reflection cracking for a 10 year period.	10
California	Nov 1977	4.0	Existing PCC overlaid with 50.8 mm (2 in) AC, fabric and 38.1 mm (1.5 in) of AC. After 4 years the pavement was in excellent condition with rare transverse reflection cracking and intermittent longitudinal reflection cracking over the longitudinal joints.	8
Virginia	Jun 1979	2.0	Control section consisted of a 38.1 mm (1.5 in) AC overlay , while the fabric sections also included the same AC thickness. Reflection cracking was significantly deterred by fabric. The overlay reflected 35% of the PCC joints, many of which were faint cracks discernible only on close inspection.	11
Illinois	Jan 1980	6.0	The original PCC pavement displayed numerous popouts. Six years after construction of the AC-fabric overlay the road shows minor joint and transverse crack reflective cracking.	12
Pennsylvania	Apr 1981	2.0	Six paving membranes were compared. There was reduction of 50% in the reflection cracks in treated sections compared to the untreated areas. Overall 38% of the transverse cracks were reflected in the control and untreated sections, while overall 18% of the transverse cracks were reflected in the fabric sections. Reflection of the longitudinal cracks was minimal in either case about 2% in the untreated and control sections and 0 % in the treated sections.	13
Texas	Jul 1981	6.0	This project consisted of repair of continuously reinforced portland cement concrete (CR CP) with placement of a fabric and a combined 88.9 mm (3.5 in) thickness of HMAC. The transverse cracks, spaced about 1 m (3.3 ft) on center, were prevalent throughout the project. After 6 years, there were few isolated transverse reflection cracks (1 every 152 m (500 ft)) dispersed throughout the project.	14
Pennsylvania	Jun 1982	3.6	A minimum of 40% less cracking was observed in the fabric sections compared to the control sections. The fabric treatment is considered cost effective.	15
California	Jul 1982	4.0	The existing PCC was overlaid with 38.1 mm (1.5 in) AC and a paving fabric. After 4 years there was little reflection cracking and the pavement was in excellent condition. The visible cracks were narrow and displayed no faulting. Evidently, water infiltration has been prevented.	8
Michigan	Jul 1982	4.0	After 4 years the average % of reflective cracking for longitudinal and transverse cracking were 36.2 and 42.5, respectively. The fabric remained intact, afforded moisture protection for the subgrade.	16

Table A.1: (continued)

Site Location	Opening Date	Time Years	Observations, Results and Comments	Reference Number
Iowa	Oct 1982	4.0	The existing PCC pavement exhibited some spalling at the transverse joints and random cracking throughout the slabs. The rehabilitation included milling of the PCC, placement of geotextile and 50.8 mm (2 in) AC overlay. The overlay survived an unusually severe winter without any signs of cracking. After 4 years transverse cracks had reflected through, but potholes or other distress were not noted.	8
Illinois	Jan 1983	4.0	Existing PCC pavement exhibited problems with popouts. The rehabilitation consisted of a 19.1 mm (0.75 in) leveling course, paving fabric and 38.1 mm (1.5 in) AC. After 4 years reflection cracking over transverse joints was observed but no popouts. The fabric provided waterproofing .	8
Belgium	Jun 1985	7.0	The existing PCC pavement was built in 1937 and heavily damaged with many cracks in the surface. The rehabilitation consisted of the placement of fabric and then 80.0 mm (3.15 in) of AC overlay. After 7 years very few cracks were observed in the fabric sections compared to the non-fabric sections.	17
Austria	Jun 1988	2.5	The existing AC overlay of PCC pavement was milled, the PCC cracks sealed, and the control section was overlaid with 120.7 mm (4.75 in) of AC while the fabric section included a leveling course, placement of the fabric and a 61.0 mm (2.4 in) AC overlay. The control and fabric sections performed equally well. The thicker control section displayed transverse crack reflection cracking of 0.5% within a year, 0.9% within 19 months and 1.8% after 30 months. The fabric section displayed transverse crack reflection cracking of 2.5% within a year, 3.9% within 19 months and 7.2% after 30 months.	18

Table A.2: Survey for AC overlay with paving fabric on existing HMA pavements

Site Location	Opening Date	Time Years	AC Overlay With Fabric on Existing AC Pavements	Reference Number
South Africa	Jun 1973	8.0	AC [50.8 mm (2 in)] overlay with fabric of existing cracked AC surface [25.4 mm (1 in) AC on cement treated base] yielded 10%, 30% and 60% reflection after 4, 5 and 8 years, respectively, of heavy traffic.	19
Colorado	Aug 1971	5.0	Control section [50.8 mm (2 in) AC overlay] developed 25% reflection cracking in a year and 80% reflection cracking in 5 years, while fabric developed less than 5% reflection cracking.	20
Florida	Aug 1971	5.0	Control section [50.8 mm (2 in) AC overlay] developed 56% cracking in three years and 100% within 4 years, while fabric section developed less than 10% in 2 years and 80% within 5 years.	20
Texas	1974	7.0	A number of sections were constructed along IH 20 at Odessa, Texas. The control section consisted of a 31.8 mm (1.25 in) AC overlay. Other sections included a 63.5 mm (2.5 in) AC overlay, fabric with a seal coat, and fabric with 31.8 mm (1.25 in) AC overlay. The fabric with 31.8 mm (1.25 in) AC overlay displayed 5% reflection cracking within 2 years and 37.5% within 7 years. A thicker AC overlay (63.5 mm (2.5 in) AC) section exhibited about 2% reflection cracking in two years and 25% within 7 years. The similarity in performance of the section with 31.8 mm (1.25 in) AC over fabric and the section with the 63.5 mm (2.5 in) overlay translates into a AC / fabric replacement thickness of about 31.8 mm (1.25 in).	14
Georgia	Sep 1976	5.8	Control sections (38.1 mm (1.5 in) AC overlay) developed 10% cracking in 1.5 years, while the fabric sections developed 2% reflection cracking within 1.5 years and 40% within 3 .75 years.	21
Oklahoma	Oct 1976	4.0	Most control sections exhibited extensive reflection cracking, while the fabric sections displayed significantly less reflection cracking (90% reduction). Reflection cracks that showed were substantially smaller than original reflected cracks in the control sections.	9
Minnesota	1976		Use of fabric reduced the amount and severity of reflection cracking by 50%.	22
Oklahoma	Dec 1976	5.0	On IH 40, fabric and control sections were constructed with 38.1 mm (1.5 in) AC overlay and a 19.1 mm (3/4 in) open graded friction course. After 6 months the control section displayed 35% reflection cracking of the transverse cracks, 0 longitudinal cracks and 0.2% of random and alligator cracking, while the two fabric sections displayed only transverse reflection cracking of 0 and 9% respectively. After a year the control section displayed 56% reflection cracking of transverse cracks, no longitudinal cracks and 8% random and alligator cracking, while the fabric sections displayed only transverse reflection cracking of 8 and 17% respectively. After 5 years the control section displayed 88% reflection cracking of the transverse cracks, 27% of the longitudinal cracks and 23.5% random and alligator cracking, while the fabric sections displayed transverse reflection cracking of 34 and 37%, longitudinal reflection cracking of 19 and 27% and 1 and 14% of alligator reflection cracking. Fabric can be used as an anti-reflection cracking treatment for both alligator and random cracking, as well as for open transverse or longitudinal cracks with widths 9.5 mm (3/8 in) or less.	9
Colorado	Jul 1977	3.3	Control section (38.1 mm (1.5 in) AC overlay) developed 10% cracking in 1.25 years and 50% within 3.25 years, while fabric section developed less than 2% reflection cracking in 1.25 years and 30% within 3.25 years.	23

Table A.2: (Continued)

Site Location	Opening Date	Time Years	AC Overlay With Fabric on Existing AC Pavements	Reference Number
California	Jan 1977	10.0	Paving fabric in an AC overlay resisted initial cracking for two to three years longer. The AC equivalent thickness for the fabric interlayer should be at least 30.5 mm (0.1 ft), but may be as much as 45.7 mm (0.15 ft) in AC overlays placed to attenuate reflection cracking. The fabric interlayer is somewhat beneficial in retarding initial cracking in AC overlays of less than 0.40 feet. There is little if any benefit of fabric for overlays of 0.40 feet or greater.	10
Colorado	Aug 1977	3.5	Control section [38.1 mm (1.5 in) AC overlay] developed 50% cracking in 1.5 years and 75% within 2.5 years, while fabric section developed less than 5% in 1.5 years and 40% in 2.5 years	23
Massachusetts	Oct 1977	3.8	Control section [50.8 mm (2 in) AC overlay] developed 42% cracking in 1.75 years and 54% within 3.25 years, while the fabric section developed 38% reflection cracking in 1.75 years and 67% within 3.75 years.	15
Georgia	Oct 1977	3.8	Control sections (38.1 mm (1.5 in) AC overlay) developed 9% cracking in 3.75 years, while the fabric sections developed less than10% reflection cracking in 3/4 year and 50% in 3.75 years.	21
Oklahoma	Jun 1978	4.0	Fabric was evaluated in stage construction of a new highway. After 4 years the control sections displayed longitudinal cracking and wheel path cracking in the driving lane, but no evidence of cracking in the passing lane. The fabric reinforced section was reported in excellent condition with no distress in either lane.	9
New Mexico	Nov 1978	4.9	Project consisted of four control sections (one with a 101.6 mm (4 in) AC overlay and three with 63.5 mm (2.5 in) AC overlay) and two fabric sections (with 50.8 mm (2 in) overlays). There was no reflective cracking in either the fabric or control sections for the initial three years. After 5 years the 101.6 mm (4 in) AC overlay control sections displayed 39% reflection cracking, the three 63.5 mm (2.5 in) AC control sections displayed an average of 23% reflection cracking, while the two fabric reinforced sections displayed 27 to 28% reflection cracking.	24
New Mexico		5.1	Project included one control section (with 139.7 mm (5.5 in) AC overlay) and two fabric sections (with 139.7 mm (5.5 in) AC overlays and fabric). Reflective cracking was not observed in either the fabric or control sections for the first two years. Within years two and three no reflection cracking was observed in the fabric sections; however, 14.6% reflection cracking developed in the control section. After 5 years the control section displayed 51% reflection cracking and the two fabric reinforced sections displayed 22 to 30% reflection cracking.	24
New Mexico		4.2	Project included one control section [with 50.8 mm (2 in) AC overlay] and two fabric sections [50.8 mm (2 in) AC overlays with fabric]. The existing pavement displayed 0 alligator cracking but numerous transverse cracking with widths between 6.4 mm (1/4 in) and 25.4 mm (1 in) which extended to depths of about 203.2 mm (8 in). During construction these cracks were not completely filled. As a result reflective cracking was observed within the first five months in the fabric sections (i.e., 5% and 12% reflection cracking) and control section (i.e., 42% reflection cracking). Within a year and a half 61% reflection cracking was observed in the control section while an average of 38.6% reflection cracking developed in the fabric sections. After 4.2 years the control section displayed 100% reflection cracking, while two fabric reinforced sections showed 80 and 100% reflection cracking.	24

Table A.2: (Continued)

Site Location	Opening Date	Time Years	AC Overlay With Fabric on Existing AC Pavements	Reference Number
Texas	1979	8.0	Project involved installation of 44.5 mm (1.75 in) AC overlays of an existing AC pavement [i.e., 76.2 mm (3 in) AC] which showed subgrade depressions and extensive transverse, longitudinal and alligator cracking in the east bound travel lane, but minimal cracking in the west bound lane. No reflection cracking was observed in the west bound lane during the initial two and a half years but increased to 39% and 60% by the eighth year. Reflection cracking in the east bound lane was less than 25% by the eighth year. The fabric sections performed little better than the control section.	14
Texas	Sep 1979	9.0	The project involved installation of 31.8 mm (1.25 in) AC overlays of an existing AC pavement [101.6 mm (4 in) AC]. The existing pavement conditions were not known. Reflection cracking was observed in both east and west bound lanes within a year. The performance of the control section in the West bound lane was better than the fabric sections, while the fabric sections performed marginally better than the control section in the East bound lane. It appears that even after cracks appear the fabric still acts as a moisture barrier.	14
Mississippi	May 1980	4.0	Control section [38.1 mm (1.5 in) overlay] developed 30% cracking in two years and 80% within 4 years, while fabric section developed less than 5% in 2 years and 20% within 4 years	25
Washington	May 1980	4.0	Control section [45.7 mm (1.8 in) overlay] developed 30% cracking in 3 years and 90% within 4 years, while fabric section developed less than 8% in 3 years and 90% in 2.5 years. The winter between the third and fourth years was one of coldest in history. The cracks were tighter in the fabric sections.	23
Oklahoma	1981	5.0	Retards reflection of block and alligator cracking; reflected transverse cracks were small in size. Reduction of AC thickness with fabric application is 25.4 mm (1 in).	26
France	Jun 1982	10.0	After 2.5 years the control (non-fabric) section displayed 30% reflection cracking, while the fabric section displayed 10% reflection cracking. After 6 years reflection cracking in the control and fabric sections totalled 51% and 30%, respectively. After 10 years the control section exhibited 65% reflection cracking, while the fabric section showed 40% reflection cracking.	1
Belgium	Mar 1987	6.0	After 6 years no cracks appeared in the fabric section. Large cracks which developed in the non fabric sections stopped at the edge of the fabric sections.	17
Spain	Jan 1988	4.0	At 3 years the fabric sections displayed no cracks, while non fabric sections displayed deflection cracking.	17
Belgium	Oct 1988	4.0	No cracks in fabric sections while cracks observed in non fabric sections.	17
France	Oct 1988	4.0	10% reflection of existing cracks as fine cracks.	17
Belgium	Oct 1988	4.0	After 4 years 0 cracks were observed in the fabric sections, while cracks appeared in the non-fabric sections.	17
Germany	Sep 1989	2.8	No cracks observed in fabric sections.	17
Belgium	Sept 1989	2.8	No cracks observed in the fabric sections.	17

Performance Expectations from Geosynthetics Manufacturers

Geosynthetics are one of the most widely used RC mitigation techniques and a number of products have been developed. Manufacturers have also investigated their products and monitored their field performance. The authors performed personal interviews with fabric manufacturers to obtain their experiences on RC mitigation. Representatives were asked to answer a few questions regarding the products they recommend for RC mitigation as well as provide any additional comments. The interview results are summarized in Table A.3 and the comments from each representative are also summarized as below.

- Mr. Mark Marienfeld, P.E. of Propex Operating Company, LLC provided a study entitled “Nonwoven paving fabrics study” performed by Maxim Technologies. This study by Maxim Technologies concluded that the use of a paving fabric interlayer has an equivalent overlay performance as 1.0 to 1.8 inches and an average thickness of about 1.3 inches (Maxim Technologies 1997). This study also stressed the importance of the water proofing benefit of paving fabrics. The overall performance of the pavement is increased when the water infiltration is decreased. In particular, rain is a prevalent concern in Florida’s road system.

- Mr. Marienfeld (Propex Operating Company, LLC) specifically recommended the Petromat 4598 from Propex and claims that the use of this fabric will double the time for cracks to return when compared to a similar control section that does not contain the fabric. He also claimed that the crack rate per year will be half of that of a similar control section.

- Mr. Gary Willibey, P.E. of Engineered Synthetic Products, Inc. recommended the use of GC130 and GC1140 and that his company’s products be installed according to installation guidelines to perform well, however he did not provide information as to what should be expected from the use of the paving fabric.

- Mr. Denis Rogers of Tencate recommended three different interlayer products for RC mitigation. These interlayers are 4.1 Oz Polypropylene fabric, 4.1 Oz Fiberglass/Polyester paving mat, and Fiberglass composite paving grid. The proper installation of these products will result in a delay of reflective cracking relative to a similar asphalt overlay without an interlayer. The cracks will take 1.6, 2.75, and 5.5 times longer to return 100%, respectively. Rogers noted that the greatest value for using an interlayer is the moisture barrier supplied by such products. Base saturation is a major factor in crack propagation. This is of considerable importance considering the Florida climate.

- Mr. Greg Kiggins supplied case studies of the use of HaTelit C 40/17 products by Huesker. These case studies indicate that the use of the product has a performance that is 3-4 times that as a pavement overlay without an interlayer.

Table A.3: Responses from fabric manufacturers

Manufacturer	Representative	Product Recommended	Time Until RC Appears
Propex Operating Company, LLC	Mark Marienfeld, PE	Petromat 4598	Using a paving fabric doubles the time before cracking returns in comparable thickness overlays with and without. Over a paving fabric the rate is half of what the same overlay would have been without the fabric.
Engineered Synthetic Products, Inc.	Gary Willibey, P.E.	GC130 and GC1140	How long after placement do reflective cracks appear depends on the existing pavement, the overlay thickness and quality, and the traffic. The same can be said for the crack rate. Rehab costs vary widely, depending on the local cost of aggregates, labor and tack coat.
Tencate	Dennis Rogers	4.1 Oz Polypropylene Fabric	1.6 times longer for 100% of cracks to return than overlay without
Tencate	Dennis Rogers	4.1 Oz Fiberglass/ Polyester paving Mat	2.75 times longer for 100% of cracks to return than overlay without
Tencate	Dennis Rogers	4.1 Oz Polypropylene Fabric	5.5 times longer for 100% of cracks to return than overlay without
Huesker	Greg Kiggins	HaTelit C 40/17	3 to 4 times as long as without the interlayer

APPENDIX B

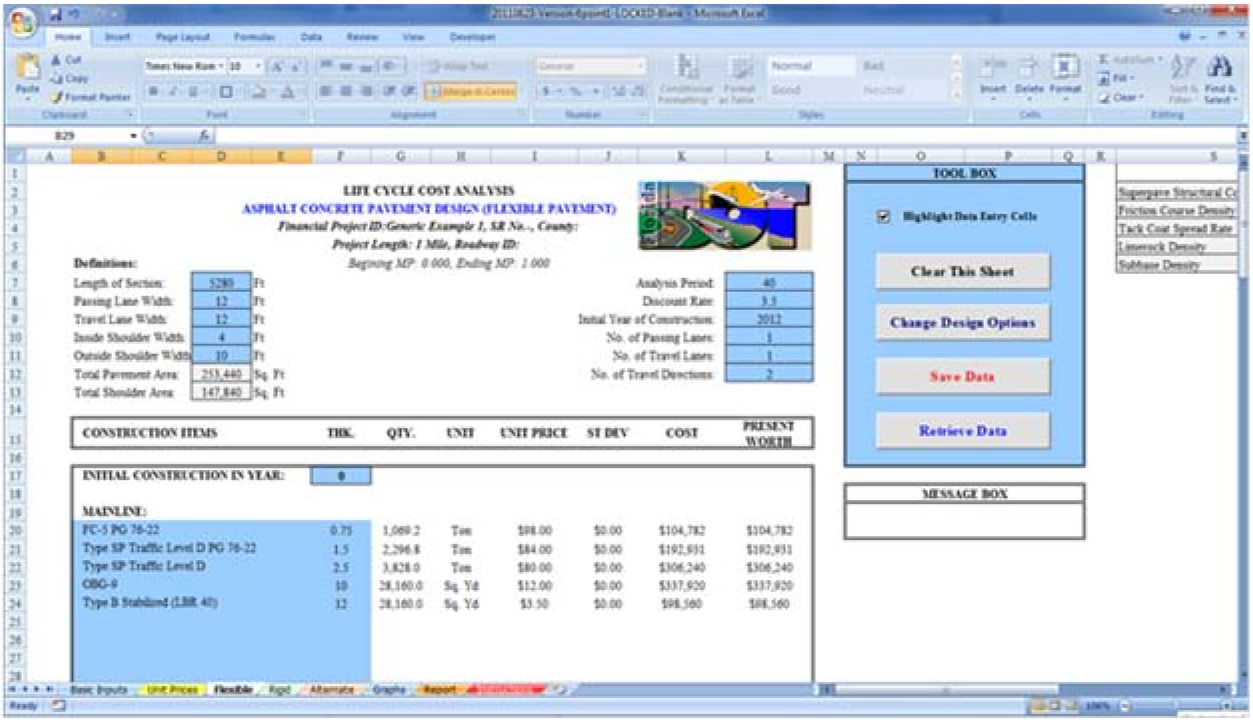


Figure B.1: A screen shot of the FDOT's custom LCCA software

APPENDIX C

<u>Construction Guidelines for Available Mitigation Methods:</u>

The reflective cracking mitigation methods investigated in this study are: (1) paving fabric (or geotextile), (2) ISAC, (3) Strata (4) chip seal, and (5) pavement recycling (both CIPR and HIPR). These are interlayer systems used to relieve the stress or strain at the tip of cracks in underlying asphalt pavements. The construction procedure of those interlayer systems is graphically explained in Figure C.1. Generally, the construction procedure of interlayers as reflective cracking mitigation methods is composed of following four steps:

Step 1: Surface preparation;
Step 2: Tack coat application;
Step 3: Interlayer placement; and
Step 4: HMA overlay.

For each mitigation method, the descriptions and design and construction recommendations are summarized as below.

(1) Paving Fabric (Geotextile)[72]

<u>Description:</u>

Fabrics are made from polypropylene or polyester. Polypropylene begins to melt at a temperature of about 325 °F; therefore, the temperature of the paving mixture or tack coat should not exceed 325°F when using polypropylene products [17].

- Geosynthetics can be effective in retarding reflection cracking from low-severity and medium-severity alligator-cracked pavements.
- Geosynthetics and other types of interlayers will typically perform considerably better in warm and mild climates than in cold climates.
- In order for geosynthetics to perform satisfactorily, the flexible pavement on which they are placed must be structurally sound.
- Surface cracks should be less than 1/8 inch wide.
- Observations have shown that fabrics are not effective where wide transverse thermal and shrinkage cracks are present.
- Geosynthetic products should not normally be placed on a milled surface. A level-up course of HMA should be placed [17, 28, 83, 84].

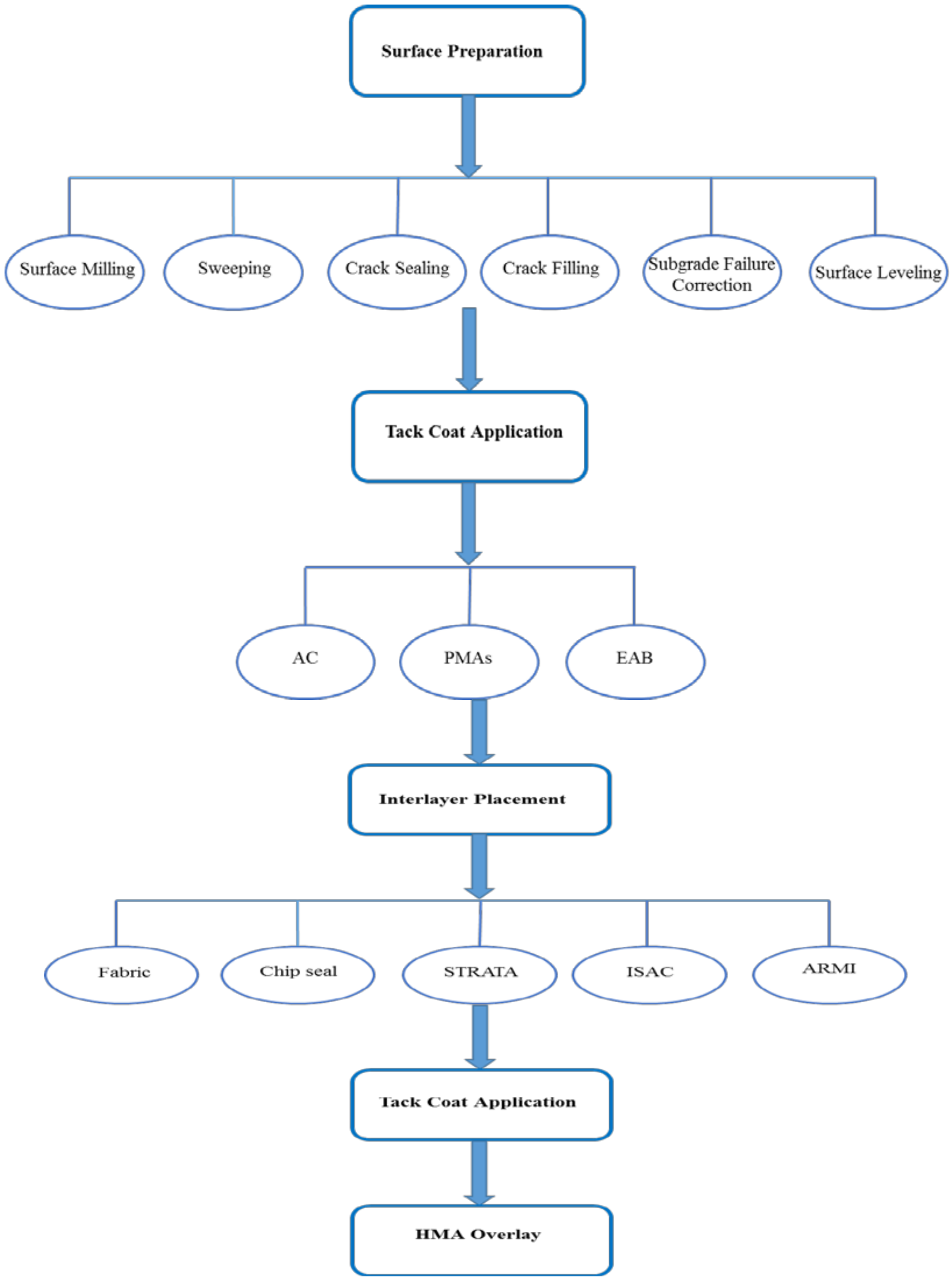


Figure C.1: Construction procedure of the selected methods

As seen in Figure C.1, interlayer systems include four steps for construction. Key considerations and construction features at each step are summarized as below.

Step 1: Surface preparation (this step applies to all other interlayers listed above):

Surface preparation is the first step for installing interlayers. If the existing surface containing severe cracks, sufficient milling depth would be required; pavement evaluation may be necessary to identify the depth of cracks. After milling, sweeping the surface is needed (several times if necessary). Cleaning surface dirt, water, and debris after milling but before tack coat is essential. After milling, if crack still exists on the surface, the following treatments are recommended specifically for fabric [14, 17, 84]:

- Cracks less than 1/8" ⟶ Do Nothing
- Cracks from 1/8" to 3/8" ⟶ Use liquid crack sealant
- larger than 3/8" ⟶ Fill with a more stable crack filler

Step 2: Tack coat selection and application:

Key considerations during the selection and application tack coat are summarized as below.

- Using hot Asphalt Cement (AC) or Polymer Modified Asphalt (PMA) tack is recommended.
- Tack should be the same grade as the binder used in the overlay.
- Emulsified Asphalt Binder are not recommended.
- Cutback asphalts should never be used with fabric.
- Application rates should be adjusted based on pavement conditions, (milled, irregular or porous and oxidized surfaces and cracked-distressed) pavement conditions. In section 334 of Florida specification required tack application rates are indicated [17, 28, 83-85].
- The amount (Gallons/Square Yard) of tack asphalt placed should be sufficient to:
  a. Bond the fabric to the old pavement (or leveling course).
  b. Saturate the fabric.
  c. Bond the fabric to the new overlay.

Steps 3 and 4: Interlayer placement and HMA overlay:

The key considerations during the placement of an interlayer and HMA overlay are outlined as below.

- Placement of the fabric shall be made only under the following conditions:
  a. The ambient air temperature is above 50 °F and rising.
  b. The pavement is dry and pavement temperature is 40°F and rising.
- The width of liquid asphalt application needs to be four inches wider than the width of fabric.
- The fabric shall overlap 2 to 6 inches at the longitudinal joints but no more than 2 inches at the transverse joints.
- Overlapped area of fabrics should be avoided joint areas.
- Transverse joints of fabric shall be shingled in the direction of the paving.
- Once the tack coat is applied, fabric can be placed after the tack coat binder is cooled down to 180 °F.
- Fabric shall not be placed in milled areas where the compacted thickness of the overlaying asphalt will be less than 40 mm in the 1st lift.
- To enhance the bond of the fabric with the existing pavement, the contractor may be required to pneumatically roll the fabric after it is placed.
- A minimum of 1.25 inches compacted asphalt overlay is required over all surfaces; this is especially important with milling only the curb areas [17, 28, 83-85].

(2) Strata [32, 86]

Description:

The Strata is an 1-inch fine aggregate HMA with highly elastic Polymer Modified Asphalt (PMA), which is an asphalt rich impermeable layer [32]. Like paving fabric, the Strata involve the three steps.

Step 1: Surface preparation
The first step is milling of existing distressed pavements. In case of structural damage in the sub-layers, the damaged layer needs to be repaired before placing the Strata. Before tack coat or Strata application, all the surfaces should be inspected in order to avoid moisture infiltration. Moisture existing will cause interlayer blistering

Step 2: Tack coat selection and application:
Some literatures suggest that a tack coat is not needed on the milled surface, however in some projects a tack coat was applied prior to the Strata application as a protective measure to minimize or prevent blistering of the interlayer [86]. Applying tack coat is also recommended in conjunction with hot weather (90 ºF or higher).

Steps 3 and 4: Interlayer placement and HMA overlay:

HMA overlay is placed on top of Strata. SBS modified asphalt mixture is the recommended HMA overlay for this system. Figure C.2, shows the flexibility illustration of Strata.

Figure C.2: Flexibility illustration of Strata

Overlay thickness:

Table C.**1**: shows the minimum overlay thicknesses recommended by SemMaterials Co. for 20 yr. traffic:

Table C.1: Minimum overlay thickness on Strata [32]

Traffic volume	Min. thickness overlay
<3 million ESALs	1.5 in.
3-10 million ESALs	2.5 in.
10-30 million ESALs	3.0 in.
>30 million ESALs	3.5 in.

Compaction:

Recommendations for the compaction of Strata are summarized as below.

- 2 to 3 static steel wheeled rollers
- First roller close to paver

- Typically 5-6 passes

Figure C.3 (a and b) shows the construction compaction of two projects using Strata interlayer.

(a) Construction compaction of Strata project (Initial stage)

(b) Construction compaction of Strata project (Final stage)

Figures C.3: Construction compaction of Strata project

(3) ISAC [14]

<u>Description:</u>

The Interlayer Stress-Absorbing Composite (ISAC) is a composite made of a low stiffness geotextile at the bottom, a highly flexible bituminous material layer as a core and a high stiffness geotextile on the top to combine the effect of both geotextile and SAMI. The construction procedure is shown in Figure C.4, (a-k) [14].

(a)Joint cleaning operation by air blasting

(b)Hot rubber joint sealant in place

(c)Tack coat application

(d)Spreading the AC cement

(e) Placement of the ISAC

(f) ISAC being rolled with a hand roller

(g) Rolling ISAC pieces with a rubber tire roller

(h) Application of the tack coat prior to paving

(i) Close-up of the tack coat application

(k) Paving over the ISAC

Figure C.4: Construction procedure of ISAC [14]

Other considerations during ISAC placement are summarized as below.

- The plastic sheeting of the ISAC has to be removed after final sweeping and right before applying tack coat, otherwise spreading dust will reduce the bonding of overlay and ISAC layer.
- Based on the WisDOT experiences, the temperature of the asphalt mix was 260º F and the ambient temperature is about 80 °F. The thickness of the overlay is ranged from 2 to 2.25 inches.[14]
- The appropriate time to use ISAC product is less than 30 days after production. It was reported that older products caused bumping on the pavement surface.

(4) Chip seal [3, 8-10, 31, 87]

<u>Description:</u>

A chip seal is a layer of asphalt binder covered by single size chips (9.5 to 12.5 mm) which are compacted and seated into the binder by a roller compactor. An HMA overlay is placed on top of it. Chip seals are categorized based on structure and can be divided into single chip seals and multiple chip seals. Chip seals can also be categorized based on the type of binder: (1) conventional chip seals, (2) polymer-modified emulsion (PME) chip seals, and (3) rubberized chip seals. The first two are mostly used as a surface treatment but rubberized chip seals restore skid resistance on worn surfaces and resist reflection cracking [3, 8-10].

Construction procedure:

The construction procedure of chip seal is presented as below. Figure C.5 (a-d) shows the construction procedure of the chip seal.

- First, cleaning the surface of road is necessary to remove debris and any holes patched.
- Second, an asphalt distributor truck begins to spray each lane with hot liquid asphalt. A chip spreader follows the asphalt distributor, and disperses the chips aggregate. The specified aggregate size varies by each state DOT; however, the recommended thickness of chip seal as an interlayer is 9.5 to 12.5 mm.
- Third, a rubber-tire roller is used to set the rock into the liquid asphalt. It takes two to four passes of the roller to set the rock.
- Fourth, sweeping the surplus aggregate and HMA overlay is a necessary step [31, 87].

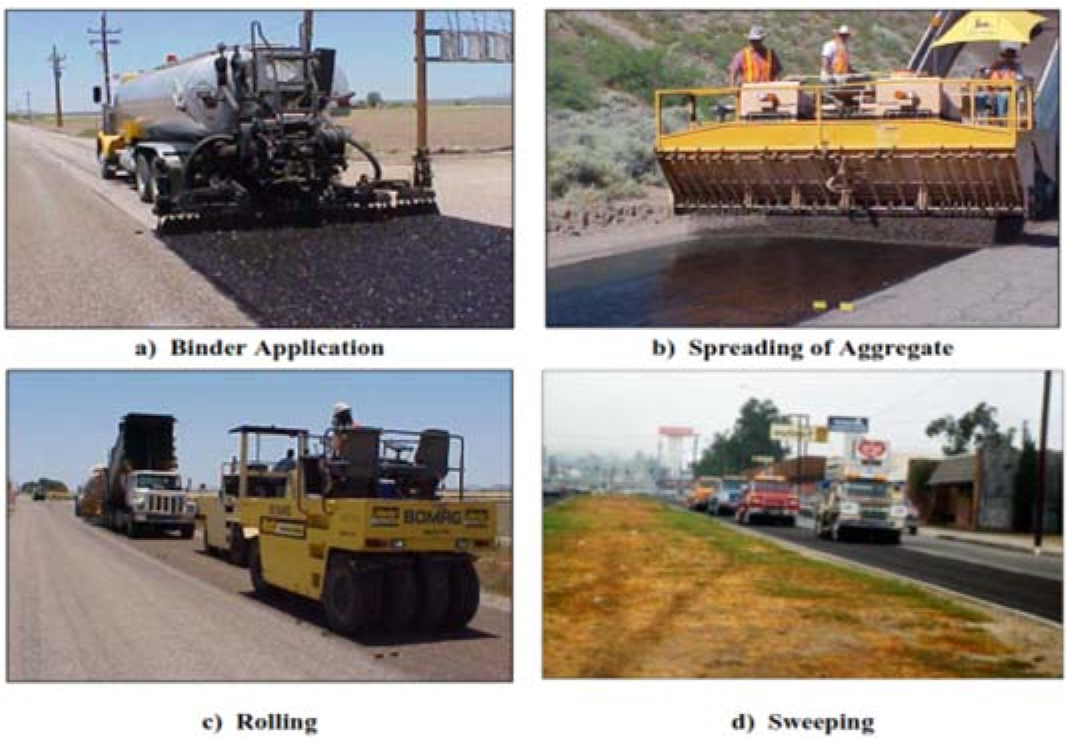


Figure C.5: Construction procedure of chip seal

(5) In-Place Recycling (CIPR and HIPR)

Asphalt in-place recycling can be (1) hot-in-place recycling (HIPR) and (2) cold-in-place recycling (CIPR). Basically, when cracks in the existing pavements are confined to the wearing surface or upper HMA layers, in-place recycling can be good candidate for rehabilitation [3].

CIPR:

Key construction features for the CIPR are summarized as below.

- The existing HMA layers are pulverized in place eliminating all cracks. A bituminous binder consisting of various emulsions or foamed asphalt (with or without cement or lime-fly ash) is normally added to the pulverized material which is compacted.
- This method is hypothesized to be a reliable technique because the reclamation/recycling process eliminates all surface cracks in the existing HMA layers, and reflective cracking becomes a non-issue [63].
- Good candidates include pavements with:
  – At least 4 inches of HMA
  – Adequate base and subgrade
  – Severe surface distresses

- Poor candidates include pavements with:
  – Inadequate base or subgrade support
  – Inadequate drainage

HIPR:

HIPR has been used in Florida [88]. Findings from the HIPR projects and recommendations are presented herein. In 2001, the FDOT constructed two projects utilizing the HIPR (remixing) process. One project included in-place milling and the other used scarification. After several weeks, the project that used in place milling experienced severe cracking; thus, the road had to be remilled and resurfaced with HMA. Possible causes of the cracking and delamination are: (1) excess dust generated by the milling head, (2) high pavement deflections at the inside wheel path, (3) in-place milling depth coinciding with the surface of the lower layer, (4) low mixing temperature, and (5) inadequate mixture properties (low AC content, high dust content, high binder viscosity). On the other hand, the project utilizing the scarification process exhibited relatively better performance, but the ride quality appeared to be below that of conventional HMA [88].

According to FDOT experience, the following is recommended:

- The recovered asphalt viscosity of the recycled mixture should be controlled by contractors to specified levels.
- Asphalt binder content needs to be monitored and controlled by contractors.
- The air void content of the recycled mixture should be monitored and controlled within the range of 3 – 5%. Low air voids and high flow can cause rutting in the future.
- Periodic inspection of the equipment (i.e., milling heads, heaters) should be routinely conducted.
- The milling depth should be specified and controlled not to coincide with the interface of any of the underlying pavement layers.