CHARACTERIZATION OF CRACK SEALANT MATERIALS AND IMPLEMENTATION TECHNIQUES

by

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DEDICATION

I would like to dedicate this dissertation to my mother (Shilpi Mazumder), father (Bhudeb Mazumder) and little sister (Tusti Mazumder).

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First of all, I would like to convey my gratitude to God. I would like to take this opportunity to express my appreciation and gratitude towards my parents, Shilpi Mazumder and Bhudeb Mazumder, for their continuous support, sacrifice, pray in order to shape my life. In addition, I would like to thank my sister, Tusti Mazumder, for her encouragement to pursue higher studies.

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ABSTRACT

Crack sealant materials are used to seal cracks early to reduce water infiltration and pavement repair. Crack sealant with high stiffness property is required due to the premature failure of sealant materials in cold weather. In order to put the sealant into the crack, crack sealing and filling technique has always been an important consideration to prolong the life of pavement. Crack sealing uses a router to cut the face of the crack to provide a uniform rectangular reservoir whereas filling is simply inserting sealant without performing any modification to the crack walls. For saving the cost of transportation agency, it is required to implement the best crack treatment techniques along with a new prospective crack sealant material.

This research investigated the prospective of a new crack sealant material and its implementation techniques, and the objectives included: 1) investigating the rheology, cracking and microstructural properties of asphalt binder modified with SIS; 2) evaluating and comparing the field performance of crack treatment techniques in Texas; 3) investigating the best cost effectiveness practice between crack filling and sealing techniques; 4) quantifying the environmental impacts of crack filling and sealing treatment.

The following conclusions were drawn based on the comprehensive laboratory and field investigation: 1) SIS modifier has the potential to be produced as a crack sealant material; 2) crack sealing treatment exhibited excellent performance and is observed to have on an average 37% more treatment effectiveness than crack filling treatment; 3) the

highway design and maintenance program (HDM-III) and field cost input analysis showed that crack sealing can be more cost effective practice in a long run compared to filling technique; 4) although the initial environmental emissions of crack sealing treatment is higher compared to filling technique, this can be compensated along with an approximately 25% reduction in emissions by implementing crack sealing treatment over a long period; 5) implementing with proper guidelines crack sealing technique is more cost effective practice in a long run compared to filling technique.

CHAPTER I

INTRODUCTION

Problem Statement

Transportation infrastructure of the United States is worth trillion dollars which includes approximately 4.1 million centreline miles of highways paved using asphalt materials (American Road and Transportation Builders Association 2015). Cracking is an inevitable phenomenon in asphalt concrete pavement and plays a vital role in pavement deterioration. Cracks develop on the surface of the pavement and indicate a reduction in pavement integrity and serviceability. It is considered as one of two main concerns in the pavement design process and the primary mode of deterioration in the pavement. Also, it is the main factor in determining time and method of rehabilitation. A crack occurs when a stress is built up in a pavement layer that exceeds the tensile or shear strength of the pavement materials. In order to delay pavement deterioration, extend service life and maximize shrinking public funds, there is no better way than doing pavement maintenance. Sealing those cracks early can reduce water infiltration and avoid the need for repairing premature base and pavement. According to National Asphalt Pavement Association (NAPA 2017), more than 94 percent highways in US are paved with asphalt materials and placing of crack sealant materials into the cracks has been a common pavement maintenance practice for decades.

Bituminous sealants are used to seal cracks in asphalt concrete (AC) pavements. Crack sealants, as defined by the American Society for Testing and Materials (ASTM) standard, are materials that provide adhesion and cohesion properties to create a barrier against the passage of liquids, solids, and gases. Over the life of the pavement, sealant should exhibit flexibility and extensibility at subzero temperatures and resist cracking at hot summer temperatures (Qadi et al. 2010). During pavement construction, sealant should flow easily into a crack and adhere to the crack wall. Bituminous crack sealants, produced with bitumen modified with polymer(s) or crumb rubber (in some cases, both), will either fail adhesively or cohesively. Cohesive failures, characterized by the fracture of the sealant in the bulk, but still adhered to the crack walls, is uncommon in cold weather locations. In contrast, adhesive failure, a debonding near the sealant/AC interface is much more common (Masson and Lacasse 1999). Despite recent advances, sealants often show premature failure and become brittle in cold weather resulting in failure. Crack sealant with high stiffness property is required to ensure the longer service period of the pavement in order to save the cost of the agency. Styrene-Isoprene-Styrene (SIS) polymer has higher aging resistance, better asphalt-aggregate adhesivity, good blend stability, and improve elastic response, superior cohesion, tensile strength and low-temperature flexibility. As a result, it is expected that the use of SIS polymer as a crack sealant product has the potential to enhance the service life of the pavement by improving the low temperature cracking resistance.

Crack Sealant failure can be explained best by the presence of defects at the sealant-AC interface such as dust, voids and microcracks. The existence of these defects is more closely related to sealant installation than to the sealant itself. There are two treatment methods for putting crack sealant materials into the cracks which are: crack filling and crack sealing. While both crack sealing and filling involve placing sealants in pavement cracks, they differ in process. Crack filling is defined as minor crack preparation, such as using an air gun to blow debris out of cracks, prior to installation of the sealant. There is no pavement removed with crack filling. On the other hand, crack sealing is defined as using a router to create a routed channel or reservoir in a crack which is then cleaned and filled with a sealant material. Both crack sealing and filling generally is carried out on structurally sound pavement which has low pavement distress by placing sealant material in the cracks. However, the reservoir configuration can help the sealant material to get good adhesion and cohesion which can increase the service life of pavement significantly resulting saving of money in a long run. Several field studies have been conducted on the sealant properties, cleaning and finishing techniques and developing the guidelines of crack filling treatment. As a result, most of the US along with Texas do not practice crack sealing treatment due to the insufficient information about its quantitative performance, guidelines and cost effectiveness. Therefore, a complete understanding of the performance of crack sealing technique compared to crack filling treatment is necessary.

Sealing of cracks is time consuming and labor-intensive routine maintenance. Haas et al. (1996) reported that the most cost expensive part of the crack treatment procedure is attributed to labor which is approximately 66% followed by equipment (22%) and materials (12%). Based on the aforementioned definition of crack sealing and filling, it is evident that the initial cost of crack sealing is higher due to the use of extra labor, material and equipment compared to crack filling treatment. Cost effectiveness of crack treatments only is analyzed based upon the field performance or prediction model rather than cost data analysis from the field. Results from the Strategic Highway Research Program (SHRP) study showed that there is almost a 40 percent greater chance of sealant success if cracks are routed prior to sealing. The initial cost of crack sealing is higher due to the use of extra labor, material and equipment. However, this treatment can give a longer service period to the pavement life cycle before the next scheduled treatment (Shuler 2009, Masson et al. 2003, Cuelho et al. 2004, Decker 2014). On the other hand, it is possible that higher initial cost treatment can be offset by the benefits of longer service period. As a result, a comprehensive study is necessary to find out the initial and long term cost effectiveness in between crack sealing and filling using modelling and real field cost data.

Preventive pavement maintenance deals with the surface refreshment to remove the early deterioration such as cracking, delay the failure and reduce the necessity for costly maintenance or rehabilitation. In the US approximately 350 million metric tons of raw materials are used for construction, rehabilitation, and maintenance of the pavement (Holtz and Eighmy, 2000). As a result, emphasis has been started to be given on the preservation of pavement in order to prolong the service period and make it more ecofriendly and cost effective. Crack treatment is one of preventive maintenance methods performed by transportation agencies in order to delay pavement deterioration, extend service life and maximize the shrinking public funds. In order to select the appropriate pavement maintenance activity, importance should be implemented on the environmental aspects along with cost effectiveness. The raw material extraction, production, construction, transportation and service period are the main cumulative contributions to the overall environmental burdens. Therefore, crack treatment methods (crack sealing and filling) needs to be quantified in terms of their environmental impact in order to find out the most sustainable treatment.

Research Objectives

The primary objective of this research is to characterize crack sealant materials and its implementation techniques. The specific objectives of this study are included:

- Investigation of the rheological properties of crack sealant material (SIS binder) through Superpave binder tests and micromorphology using micro and nanotechnology,
- Evaluation of the field performance of crack treatment techniques (crack filling and sealing treatment) in asphalt pavement of Texas,
- Evaluation of the initial and long term cost effectiveness of crack filling and sealing treatment,
- Investigation of the environmental emissions of crack filling and sealing to the environment.

Scope of Research

The objectives of this study are accomplished through the completion of the tasks described below:

- Evaluating the viscosity property (blending time: 80 minutes; SIS percentage: 0, 5, 10, 15, and 20% by the binder weight) in the laboratory using
    - A rotational viscometer.
- Evaluating the rheological property (SIS percentage: 0, 5, 10, 15 and 20% by the binder weight) in the laboratory using

- A dynamic shear rheometer (DSR), and
- A bending beam rheometer (BBR).

- Evaluating the micromorphology of the binder using Atomic force microscopy (AFM), Environmental Scanning Electron Microscopy (ESEM), and Ellipsometry.

- The distribution of survey questionnaires and the installation of both crack treatment types in four districts of Texas based upon the various climate, average daily traffic and pavement conditions, and the regular inspection of the field performance of both treatment type.

- Evaluating the cost effectiveness of crack treatment methods using highway design and maintenance standard model (HDM-III) and real field cost input (sealing time, labor, material, equipment, and traffic, etc).

- Developing a life cycle inventory and evaluating the impact assessment on eight impact categories.

Dissertation Organization

This dissertation consists of eight chapters. Chapter I presents the background, objective and scope of the study. Chapter II is a literature review of previous research on sealant materials, different crack treatment methods, practices in Texas and US. Chapter III summaries the statistical methods used for analyzing data. Chapter IV contains the physical, rheological and microstructural properties of crack sealant materials depending upon SIS contents. Chapter V describes the sealant application methods and its performance. Chapter VI reports the cost effectiveness of sealant application methods. Chapter VII includes the environmental impact of crack sealant techniques. Finally, Chapter VIII includes a summary of the investigation, conclusions, and provides recommendations for future research.

CHAPTER II

LITERATURE REVIEW

Crack Sealant Materials

Crack sealant is the material that is inserted into pavement cracks in order to prevent entry of water, contaminants and pavement deterioration. The type of sealant depends on the type of pavement, and there are currently two method of crack sealant, hot pour and cold pour. The most common type of hot pour sealant is hot poured rubber, though there are rubber-asphalt combination materials. Cold pour is generally a polymer-modified asphalt emulsion. Hot pour is the most used method in Texas. Yildrim et al. (2006a, 2006b) compared hot rubber sealants to cold emulsified crack sealants for their 4-year study. They found that hot pour sealant outperformed cold pour and cost less than cold pour sealant. To get appropriate service, the sealant must be correctly applied.

The material application is critical to its performance. Crack seal often comes in solid blocks, which are then placed into a giant melting pot to be liquefied for application. Naturally, it would seem that the hotter the material, the more fluid it becomes, and the easier it is to apply. This is true, however heating the material above the manufacturer's recommended levels, especially for sustained periods of time, degrades the materials so that they do not function properly once they cool and solidify into the cracks (Masson et al. 1999). Besides the temperature, the amount and finish of the material is important. It is important to note that treatment can only stop certain cracks from progressing and continuing to deteriorate the road surface quality. Only transverse, longitudinal, block, and reflective cracking should be sealed. Alligator cracking represents a base failure, and treating it would not be cost effective (Eaton & Ashcroft, 1992; Ward, & Fang, 2000).

Crack sealant is considered failed when it no longer keeps out water and other contaminants, or when it no longer "seals out" material. The application of the crack sealant can impact the ride quality of the road. When crack sealant is applied, it is pumped into the crack, and can be left just below the surface of the pavement (creating a shallow canal), leveled at the pavement (using squeegees; also called "flush fill"), or filled to just above the pavement surface (creating a slight bump on the pavement; also called "overbanding") (Caltrans, 2003). In general, sealants are composed of bitumen, styrene butadiene copolymer, and filler. The styrene-butadiene (SB) copolymer consists of linked blocks of polystyrene (PS) and polybutadiene (PB). According to Becker et al., (2001), it is the most appropriate and used polymer for asphalt modification, followed by reclaimed tire rubber. It is the formation of critical network between the binder and SBS that increases the complex modulus, resulting the increase in rutting resistance. In 2004, Florida Department of Transportation and FHWA reported that SBS benefited the cracking resistance by reducing the rate of micro-damage accumulation (Roque et al., 2004). However, the addition of SBS has some drawbacks in terms of economic and technical limits. It is capable to increase the low temperature flexibility but some authors report that a decrease in strength and resistance to penetration is observed at higher temperature (Yildirim et al., 2007).

The fillers may include ground tire rubber, mineral fines, calcium carbonate, and fibers. On the other hand, SIS polymer has the potential to overcome the challenge of current crack sealant materials (low temperature failure and cracking) due to its high stiffness and elasticity. SBS (styrene-b-butadiene-b-styrene) has butadiene as rubbery mid-block whereas SIS (styrene-b-isoprene-b-styrene) has isoprene as rubbery midblock. The

SIS molecule chain is composed of isoprene. It increases the complex modulus at high temperature and due to its branch methyl in the isoprene group it has better tenacity and compatibility with other materials (Zhang 2017).

Crack Sealing and Filling

Cracking is an inevitable problem in asphalt concrete pavement and it indicates a reduction in pavement integrity and serviceability. The different types of crack formation are recognized as transverse, longitudinal, fatigue, block, reflective, edge and slippage, and each has their own causes. It is considered as one of the two main concerns in the pavement design process and the primary mode of deterioration in the pavement. Also, it is the main factor in determining time and method of rehabilitation. A crack occurs when a stress is built up in a pavement layer that exceeds the tensile or shear strength of the pavement materials. In order to delay pavement deterioration, extend service life and maximize shrinking public funds, there is no better way than doing pavement maintenance. There are various types of pavement maintenance activities such as total surface seals, resurfacing, crack sealing or filling. The main goal of these surface treatments is to minimize the intrusion of water through cracks into underlaying layers which can lead to pavement structural failure. Among these surface treatments, sealing the crack with sealant material has been a common pavement maintenance practice for decades.

Crack sealing is the process of routing and placing sealant material in the routed channel. This is opposed to crack filling, which is simply inserting sealant without performing any modification to the crack walls. Sealing cracks can reduce the water infiltration, prevent pumping and avoid the need for premature base and pavement repair. Although it has advantages, it can affect the pavement in many ways such as tracking of scaling material by tire action, reduced skid resistance and a rougher pavement. Sealing of crack is the logical alternatives compared with other maintenance program due to its economic benefits, improving serviceability and vital role in extending the life of pavement (Eaton et al. 1992). The practice of sealing cracks will keep improving in terms of the durability of sealants and its implementation techniques. Proper planning, design and implementation of sealing techniques can ensure the longevity of the pavement as well as maintain a higher standard of ride ability over a longer period of time. The objective of the chapter is to provide a review on the different aspects of the crack treatment methods along with different state practices in US. The analysis and details of the different aspects of crack treatment methods can be a significant value to the researcher to investigate the limitation of the earlier study and field personnel to select the proper cost effective treatment.

While both crack sealing and crack filling involve placing sealants in pavement cracks, they differ in process. Generally, and for the purposes of this dissertation, crack sealing is defined as using a router to create a reservoir in a crack which is then filled with a sealant material. Crack filling is defined as minor crack preparation, such as using an air gun to blow debris out of cracks, prior to installation of the sealant. There is no pavement removed with crack filling. Apart from that crack sealing and crack filling is also known as the routing and non-routing configuration of crack sealing, respectively. Additionally, crack sealing is performed on working cracks, whereas crack filling is generally the term used to refer to the treatment of nonworking cracks (Caltrans 2003).

Crack sealing is used to treat the active cracks which open in winter and close in summer, known as working cracks. According to the Masson et al. (2003), working cracks are typically greater than 3 mm (0.12 in) in width in the summer and 15 to 100 percent larger in the winter. According to NCHRP 784, “1999 LTPP report, the FHWA defined the movement for “working” classification as 2.5 mm; however currently the value most commonly referenced is 3 mm or approximately 1/8". According to the Federal Highway Administration Manual of Practice, transverse cracks which are perpendicular to the traffic direction are considered as working cracks and are often targeted for crack sealing (Zinke et al. 2005; Hand et al. 2000). Working cracks are routed to a predefined geometry, cleaned and materials are placed into it in order to prevent the intrusion of water into the pavement surface through the upper surface. Routs are generally given with a width to depth ratio of one or greater than one that can enhance the sealant performance (Wang and Weisgerber 1993; Ketcham 1996; Khuri et al. 1992). This treatment can be more effective when applied to pavements which are in good condition with low to moderate crack density and where cracks show little or no branching (FHWA 1998). The treatment of crack treatment is widely used as a component of Pavement Management Systems (PMS), though is not a comprehensive treatment in and of itself (Hu et al. 2012). Successful implementation of both these treatment applications depend on the appropriate selection of pavement and material, crack preparation and crack sealant application.

Crack Types and Development

The intrusion of water causes various distress mechanisms which can lead to the damage of the pavement structure. Crack types include fatigue cracks, longitudinal cracks, transverse cracks, block cracking, reflective cracks, edge cracks and slippage cracks.

Fatigue cracks

Fatigue or alligator cracking is a series of closely spaced inter connecting cracks resulting from repetitive traffic loads or high deflections caused by failing base, sub-base or sub-grades. Generally longitudinal cracks in the wheel paths are considered as the first visible sign which can lead to alligator cracking. This type of cracking is a cause to potholes and pavement disintegration and it cannot be remediated by crack sealing or filling treatment.

Longitudinal cracks

Longitudinal cracks develop between edges of the pavement and are caused by thermal movement or by poorly constructed construction joints between adjacent travel lanes or between a travel lane and the shoulder. Longitudinal cracks are considered as ‘non-working’ cracks and generally can be effectively treated by crack filling.

Transverse crack

Transverse cracks occur perpendicularly to the center line of the pavement. These types of cracks form due to the thermally induced shrinkage at low temperatures. Transverse cracks are considered as “working” cracks and suitable type of distress for crack sealing.

Block cracking

These type of cracks are interconnected and look like rectangular blocks caused by age hardening of the asphalt coupled with shrinkage during cold weather. These cracks can be effectively treated with crack sealants depending on the crack treatment methods.

Reflective cracks

Reflective cracks are caused by cracks or other discontinuities in underlying pavement and/or soil layers that propagate up through due to movement or differential stresses across the crack. It can exhibit any of the crack patterns mentioned above.

Edge cracks

Edge cracks are crescent shaped or parallel cracks located within 0.3m to 0.6m of the outer pavement edge. These cracks are caused by overloading at the unbound edge of the pavement, shear failure, tree and plant roots, or erosion in the shoulder.

Slippage cracks

These cracks are caused by the separation of top asphalt layer and underlying material due to high deflections and poor bond between the layers. These cracks cannot be effectively treated with crack sealing or filling.

Planning, Design and Implementation

Time of year and temperature

The time of year and ambient temperature plays a vital role during the application of crack sealing and filling treatment. Eaton et al. (1992) suggested three variables to consider before crack treatment which are: when the cracks at their best width, time of year when crews are available, temperature range for sealant application. For hot climates they recommended winter is best as the cracks are open and the highway crews are available, for colder climates late fall and early spring will give the best results. They concluded with a safe thump rule that colder months (40^{o}-75^{o}F) are appropriate for crack sealing. Yildirim et al. (2006) suggested that crack sealing should be done during the winter months when the cracks are open so that sealant can more easily penetrate the crack. It was mentioned the temperature should be between 45 and 65 degrees Fahrenheit. According to the Masson et al. (2003), crack treatment should be performed in spring or fall when temperature are moderate and cracks are mid-course in their annual cycle. It was also mentioned that summer can be a good option in terms of sealant installation due to the low humidity in asphalt concrete surface and morning temperatures are the highest. They concluded that the selection time is a compromise between the effect of crack movement on sealant performance and sealant installation. According to NCHRP report 784 (2014), the temperature for performing crack treatment was recommended from 40-70°F because cracks become wider during cool temperature. Based on the aforementioned discussions it can be deduced that spring and winter months are proper time to conduct crack treatment. Figure 2-1 presents the effect of crack opening and time of work on sealant material based on crack or rout width.

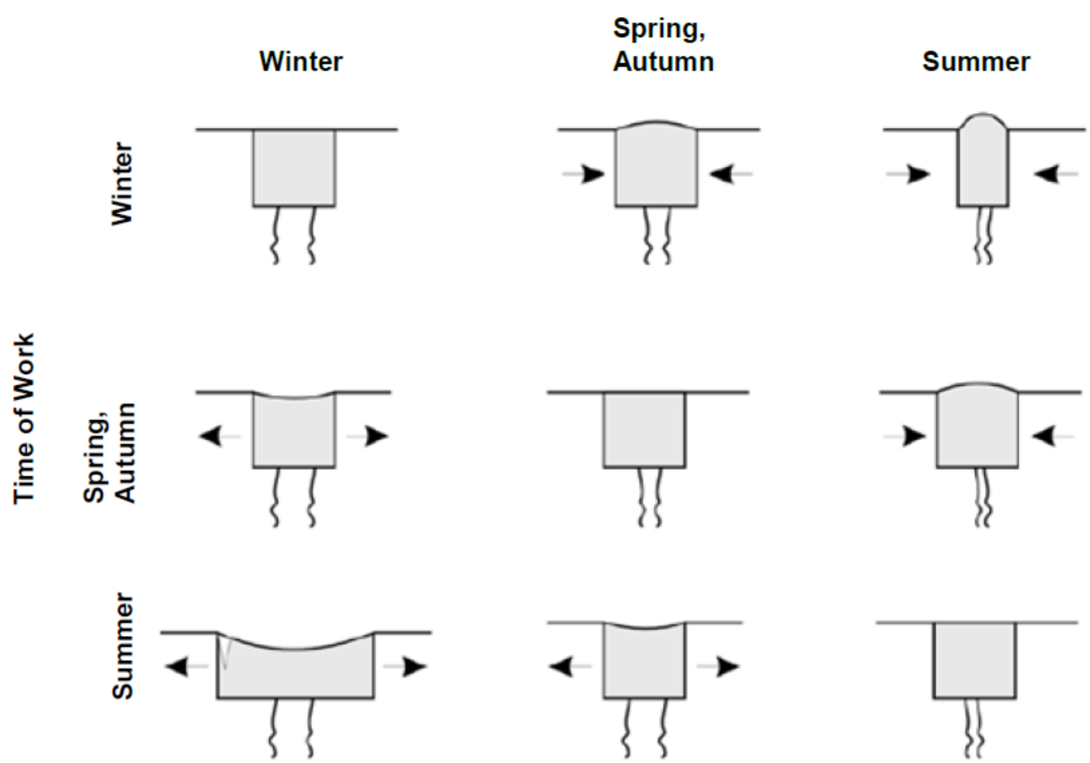


Figure 2-1. Seasonal impact on sealing operations (NCHRP Report 784)

Traffic control, safety and contracting procedure

Traffic control is one of the most important practices during the implementation of crack treatment; this practice ensures the safety of all workers. Proper traffic control devices should be installed during crack treatment. Traffic control devices shall be carried out in accordance with agency requirements or the Manual on Uniform Traffic Control Devices. In Texas, traffic control devices guidelines are provided by the Texas Manual of Uniform Traffic Control Devices (MUTCD) (Yildirim et al. 2006). Traffic volume and curing time should be considered when developing the traffic control plan. Collins et al. (2006) suggested that the roadways with treated cracks may be reopened to traffic after 15 minutes, for greater benefit to motorists but this is material and weather dependent.

Crew safety is a major concern while doing crack sealing. Routers, air lances and hot compressed air lances (HCL) should be used according to manufacturer's recommendations. During the application of crack sealing, construction workers should wear safety apparel such as long sleeved shirts, leather gloves, steel toed boots, hard hats, safety vests and adequate eye protection. All safety precautions should be taken during material handling and operation of the equipment (Yildirim et al. 2006).

These are two types of contracting procedures available. One is that the agency will self-perform the crack treatment installation and the second is that the agency will contract an external company for the crack treatment services. Generally unit price, lump sum, cost plus, indefinite delivery and warranty methods are used when giving contracts to another agency. The selection of the best method depends on the economical consideration. According to NCHRP Report 784 (2014), TxDOT provides the contractor with material for the crack treatment which protects the contractor in terms of risk associated with quantity of materials. Michigan DOT uses a warranty method. According to their survey the average length of warranty was 1.4 years.

Pavement selection

Crack sealing can be a useful preventative maintenance activity if the selection of the pavement is proper. The crack sealing and filling treatment should be carried out on structurally sound pavement which has low pavement distress (Masson et al. 2003; Caltrans 2009). According to SHRP-H-348 (1993) the pavement selection consideration should be based on pavement age, pavement and geometric design, pavement selection boundaries, traffic, type and extent of previous maintenance treatments and condition rating. It also suggested a shoulder survey should be performed on a small pavement selection, about 500 ft (153 m) in order to determine the amount, type and condition or severity of cracks, as well as the effectiveness of any previously applied crack treatments. According to the Asphalt Crack Sealing Practices and Processes (Murray 2013), the best candidates for crack sealing and filling are newer pavements which are in the range of 1 to 3 years and the majority of pavement distress can be found in terms of longitudinal or transverse cracks having slight to moderate crack density. According to Masson et al. (2003), crack sealing and filling is first done on pavements that are three to five years old. Table 2-1 presents the description of crack width and density.

Caltrans has their own cracking criteria for crack treatment. NCHRP Report 784 (2014), tabulated the appropriate crack types for routing (crack sealing) and non-routing (crack filling) configuration of crack treatment according to their survey response. Table 2-2 presents the criteria for crack sealing.

Table 2-1. Classes of crack widths and densities (Chong et al. 1989)

Crack	Class	Description
Width	Slight	2 to 12 mm single crack.
	Moderate	13 to 20 mm single or multiple cracks. Crack below 20 mm that show cupping or lipping.
	Severe	Single or multiple cracks with cupping and lipping or cracks larger than 20 mm. Crack below 20 mm that show spalling.
Density	Intermittent	No set pattern. Less than 20% of pavement surface is affected. Transverse cracks are 30 to 40 m apart.
	Frequent	20 to 50% of surface is affected. Longitudinal cracking can be localized or distributed evenly over pavement section. Transverse cracks are 20 to 30 m apart.
	Severe	Cracking is distributed evenly over more than 50% of pavement surface. Transverse cracks are 10 to 20 m apart.

Table 2-2. Crack sealing criteria

Crack Characteristics	Crack treatment			
	CalTrans cracking criteria	Yildirim et al. (2006)		NCHRP-784 survey responses
		Routing	Non rouitng	
Width (inch)	0.12-1.00	0.2 to 0.75	0.2 to 1.0	0.24-1.01
Depth (inch)				0.72-3.00
Edge Deterioration	<25%	Minimal to none ≤25% of crack length	Moderate to none ≤50% of crack length	
Annual Horizontal Movement	>0.12 Working	≥0.1	<0.1	
Type of Crack	Transverse Thermal Transverse Reflective Longitudinal Reflective Longitudinal Cold Joint	Transverse Thermal Transverse Reflective Longitudinal Reflective Longitudinal Cold Joint	Longitudinal Reflective Longitudinal Cold Joint Longitudinal Edge Distantly Spaced Block	
Time since last treatment				4.5 (years)

Pavement distress can be assessed from the Pavement Condition Rating (PCR) or Pavement Serviceability Rating (PSR). MTO (1990) provides a typical PCR scale with some pavement characteristics. Table 2-3 presents the pavement condition ratings.

Table 2-3. Typical pavement condition ratings (MTO 1990)

PCR	Description
100-90	Pavement is in excellent condition with few cracks. Rideability is excellent with few areas of slight distortion.
90-75	Pavement is in good condition with frequent very slight or slight cracking. Rideability is good with intermittent rough and uneven sections.
75-65	Pavement is in fairly good condition with slight or very slight dishing and a few areas of slight alligatoring. Rideability is fairly good with intermittent rough and uneven sections.
65-50	Pavement is in fair condition with intermittent moderate and frequent slight cracking and with intermittent slight or moderate alligatoring and dishing. Rideability is fair and surface is slightly rough and uneven.

Zinke et al. (2005), mentioned that PSR numbers range from 1 (worst) to 9 (best) and a PSR number of 6 to 7 can be a suitable candidate for crack sealing and filling treatment. PSR numbers are based on the five criteria which are cracking (25%), distortion (15%), disintegration (30%), drainage (20%) and ride (10%). If there is a plan to do a seal coat or overlay on a pavement, crack treatment should be completed 6 to 12 months prior in order to reduce the potential for bleeding of the sealant through the subsequent surface layer (Yildirim et al. 2006).

Sealing Methods

Selection of a placement configuration depends upon four variables.

a. Type of application or distress

b. Type of crack channel (cut or uncut)

c. Strike off or finish characteristics (recessed, flush, capped, band-Aid)

d. The dimensions of the crack channel

Typical placement methods used on flexible pavements are grouped into four categories

1. Flush-fill
2. Reservoir
3. Overband
4. Combination (reservoir and overband)

In the flush-fill configuration, material is simply forced into an existing crack and once filled, the crack is struck off flush with the pavement. Generally this configuration is used prior to placement of a surface treatment. This configuration type can ensure smooth ride experience to the driver.

Generally reservoir method is used for working cracks. In a reservoir configuration, the crack is cut or routed to form a crack reservoir that is filled with a sealant. Material can be placed in either a flush or recessed configuration. Johnson et al. (2000), stated that routing transverse cracks improved sealant performance but routing of longitudinal cracks was not necessary.

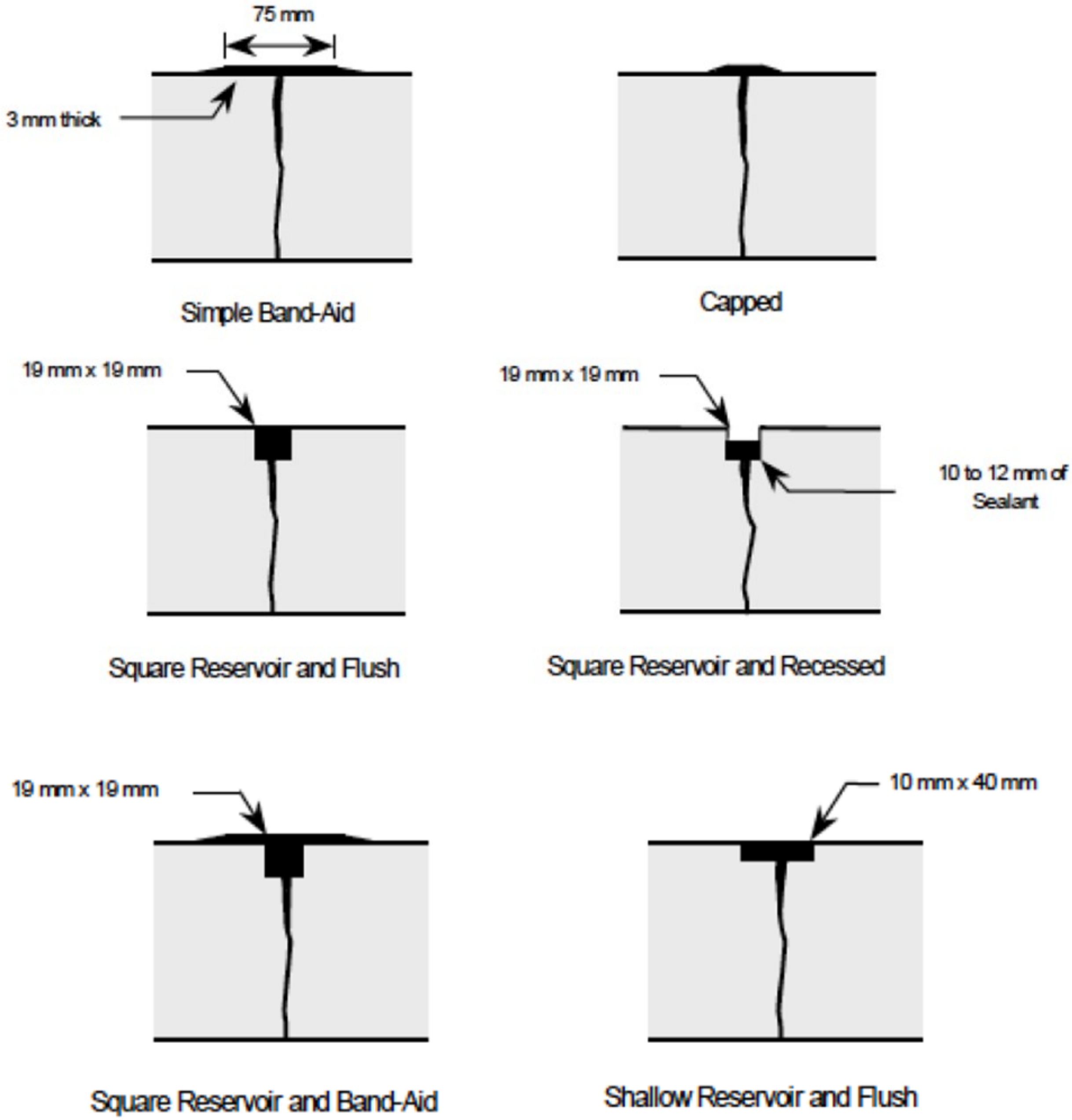


Figure 2-2. Crack sealing techniques (Cuelho & Freeman 2004)

In an overband method, material is forced into and placed over an uncut crack. If the material is shaped into a band using a squeegee, it is referred to as a "Band-Aid" configuration. On the other hand, if the material over the crack is left unshaped than it is known as capped configuration. With this configuration type drivers are likely to experience roughness.

The combination method involves the formation of “Band-Aid” by placing the material into and over the top of a cut reservoir. A squeegee is used to shape the material into a “Band-Aid” configuration. The dimensions of the band-aid are typically 3 to 5 in (76 to 127 mm) wide and 0.125 to 0.188 in (3.2 to 4.8 mm) thick (SHRP-H-348). Shuler et al. (2009) installed crack sealant on three sections with overbanding, flush fill and recessed configuration after routing the cracks. They concluded that overbanding and flush filling of the crack sealant after routing the crack appears to provide similar performance in two sections but in another section overbanding after routing outperformed flush filling after routing. Figure 2-2 illustrates the different types of placement methods for sealants.

It is apparent from looking at Figure 2-2 above that drivers are more likely to experience roughness from recessing or overbanding than from flush filling the cracks, regardless of whether it is routed or not. This is confirmed by Caltrans (2003), who say that “overband treatments have contributed to poor ride, ride noise and poor surface appearance and are not recommended for use unless it has been squeegeed flush to the surface of the road”. As a roads roughness is an indicator of condition, it makes sense that crack treatment methods which utilize a higher-than-the-surface profile on the road will negatively impact driver perception. Additionally, the faster a car is going, the more it feels the road roughness (or smoothness), so crack seal methods used on a higher volume roads will likely cause more user dissatisfaction than the same crack seal methods used on a road with a lower speed limit.

Figure 2-3. Squeegee for sealant

Therefore, overband should be used only on low speed roads that will not be overlaid within in six months (Caltrans 2009). Cheovits and Manning (1984) stated that overband configuration has disadvantages like aesthetics, exposure of the surface sealant to environmental and traffic deterioration and the large and localized tensile strain that develop above the crack. Also, Eaton and Ashcraft (1992) mentioned that overband should not be used on city streets, parking lots or sidewalks as the materials are prone to pick up due to traffic, resulting in material tracking. So, whether it is a routed or non-routed configuration, care must be taken to squeegee excess material off the surface after placing the sealants. Figure 2-3 presents the squeegee for sealant.

<u>Routing</u>

Routing incorporates the use of a router to open all the cracks up to a uniform width and depth, though the two may not be same, and are determined based on the job. The objectives of doing routing include a) cutting the crack faces back to sound pavement, and b) providing an adequate width of sealant to accommodate crack movements without over extending the sealant It is extremely important that routs should be square or rectangular because rounded bottoms and V shaped routs create debonding issues (Wang and Weisgerber 1993). The procedure of routing helps to create uniform and smooth edges which ensure proper adhesion of sealant material with the asphalt pavement. A router is a machine that operates using either carbide teeth or carbide tipped bits. They can look like lawnmowers or small-to-medium push-blowers, but are not large or bulky like a paver or a truck. Router must be designed to follow wandering cracks without tearing, chipping or spalling the crack edge. It can produce an appropriate geometry in a single pass and should be capable of centering the cutter evenly over the rout.

As it is very difficult to accurately follow the meandering cracks with a router, portions of crack may be missed and it can create two adjacent channels. Also, it can cause additional damage on the pavement as it is the slowest activity in sealing operations. As a result, it is very important to use a high production machine that follows cracks well and produces minimal spalls or fractures.

Conn DOT specifications required that the crack routing should be conducted with a vertical spindle or rotary type cutter in order to protect the pavement from unnecessary damage. The FHWA Manual of Practice recommends crack routing over saw cutting because cutting cannot follow the path of the crack as well as routing. According to SHRP-H-348 (1994), carbide router bits are highly recommended over steel router bits. Figure 2-4 shows the router machine.

Routs can be done either on a 1x1 profile (cutting as wide as deep) or 2x1 or 4x1 profile. Routing with a 2x1 or 4x1 profile can follow meandering crack better (Eaton & Ashcraft, 1992). Routing with a width/depth greater than or equal to a ratio of one can enhance sealant performance but excessive widths are not desirable as they provide greater sealant exposure to slow moving traffic and raise failure rates (Masson et al., 1999). Good performance is obtained with routs of 30 by 15, 25 by 12 and 12 by 12 [W(mm) x D(mm)] but rout widths should not exceed 30 mm (National Guide to Sustainable Municipal infrastructure, 2003).

Figure 2-4. Carbide-tipped rotary impact router bit

According to NCHRP Report 784, routers should remove 1/8" from each side of the crack. The minimum and maximum widths of the cut are suggested as 1/2 " and 1-1/2", respectively, with a recommended cut depth of 3/4". Stevenson et al. (2001) recommended minimum reservoir widths with recommended depths, for various climates. Table 2-4 shows the information.

Table 2-4. Reservoir width & depth (Stevenson et al. 2001)

Climate	Minimum Reservoir Width	Recommended Reservoir Depth
Warm	1/2"	3/4"
Moderate	3/4"	3/4"
Cold	1-1/8"	1/2"
Very cold	1-1/2"	3/8"

For milder climates Chong and Phang (1988) stated that a rout of 19 mm x19 mm is also acceptable. Chong (1990) indicates that for urban expressway a rout configuration of 12 mm x12 mm works well. Ponniah and Kennpohl (2007) recommends routing cracks between 3mm and 19mm wide to a configuration of 40 mm x 10 mm. Filice (2003) recommends a 40 mm x 10 mm rout for transverse cracks and a 40 mm x 15 mm rout for transverse cracks where the pavement has a chip seal. Caltran division of maintenance

(2009) recommends dimensions for routing and sawing. Table 2-5 presents recommended dimensions for routing.

Table 2-5. Recommended Crack routing and sawing dimensions (Caltrans, 2009)

Nominal Crack Width*	Rout or Saw Width	Rout or Saw depth**	Width in Areas of Temp extremes	Depth in Areas of Temp extremes**
¼ inch	½ inch	½ inch	1 inch	½ inch
3/8 inch	½ inch	½ inch	1 inch	½ inch
½ inch	¾ inch	¾ inch	1 inch	½ inch
⅝ inch	¾ inch	¾ inch	1.5 inches	¾ inch
¾ inch	No routing required	¾ inch***	1.5 inches	¾ inch
⅞ inch	No routing required	¾ inch***	1.5 inches	¾ inch
1 inch	No routing required	¾ inch***	1.5 inches	¾ inch
* Nominal crack width is the approximate width for 80% of the length of the crack				
**If using recessed fill method, add ¼ inch				
***Use sand fill or backer rod to limit material depth to ¾ inch				

Proponents of routing say there are several benefits, including: opening small cracks and allowing for greater penetration of the sealant, producing uniform edges and cracks, and it allows the cracks to be filled to at or just-below pavement surface level (Eaton & Ashcraft 1992). There are also negative aspects to routing, including that it is labor intensive (and therefore expensive), difficult to follow and route all cracks, slow, exposing the crew to potentially dangerous situations for longer periods of time, requires a follow up process (being blown out with compressed air), and in pavements older than six or seven years, routing may cause additional cracking in the surrounding pavement (Eaton & Ashcraft 1992; Masson & Lacasse 1999). On the other hand, it is not practical to do routing to the hair line cracks. Also, if there are only few cracks suitable for routing, the operation may not be economically viable conversely, if the cracking is very extensive, routing may not be the solution (Hajek et al. 1987). As a result proper guideline for doing routing is very important.

Recently, Solanki et al. (2014) conducted field studies in Minnesota, New Hampshire and Ontario to evaluate the effect of different installation parameters consisted of 38 sections containing a total of 487 cracks. According to the preliminary results and analysis within two years after installation they concluded that the rout geometry with 12.5mm x 12.5mm showed best performance among all the rout geometries due to the least exposure to weathering and slow-moving traffic. Sealants that were installed by the rout and seal method showed good performance compared with their clean and seal counterparts on the same test section.

The literature review is very limited considering the guidelines, benefits and cost effectiveness of crack sealing (routing) compared to crack filling (non-routing) configuration.

Crack preparation for sealing

Crack cleaning and drying process are the most important phase of a successful crack treatment implementation because wet or dirty channels result in adhesion failures between the sealer material and the sidewall of the crack (FHWA Manual of Practice 1999). According to Masson et al. (1999), high percentage of sealant material failure can be attributed to adhesion failure due to dirty or moisture cracks. Debris also causes cohesion failure by contaminating the sealant materials. In order to avoid cohesion and adhesion failures, sawed or routed cracks must be cleaned before sealant treatment. Yildrim et al. (2006) recommended that cracks should be cleaned to a depth of at least twice the crack width. According to FHWA Manual of Practice, four methods used to clean the cracks which are:

1. High pressure air blasting
2. Hot air blasting (HAL)
3. Sand blasting
4. Wire brushing

High pressure air blasting equipment is effective and efficient for removing dust, debris and some loosened AC fragments. However it cannot remove the laitance or dry the crack channel. (SHRP-H-348). A compressor equipped with oil and moisture filters should have a minimum blast pressure of 100 psi or 670-700KPa with a blast flow of 150ft^3/min or 0.07m^3/s (National Guide to Sustainable Municipal Infrastructure 2003; Caltrans Division of Maintenance 2009; Wasieleski 2005).

HAL can be used after the application of high pressure air blasting in order to dry the crack. It could provide two key benefits: (1) by removing the moisture from the crack and (2) promoting enhanced bonding associated with the crack edges being warmed. It is capable of providing some heat to the rout surface and useful for the removal of some humidity (Masson et al. 2000; Smith et al. 1993b). The HAL is not a cleaning tool and the temperatures should be kept below 500^{o}C (932°F) with a maintaining tip distance 5cm to 10cm from the crack or rout (National Guide to Sustainable Municipal Infrastructure, 2003). Crafco recommends the air temperature of HAL should not exceed 400 ^{o}C (750°F) (NCHRP report 784).

The color of the hot end of the HAL is a good indicator of its temperature. If it is bright orange to bright red, the temperature is 600^{o}C to 1100^{o}C; if it is dark red then

500°C to 600°C and if it is black then 400°C to 500°C. Caution must be taken so that overheating of the rout or crack should not take place. Overheating of the pavement leads to unnecessary hardening of the asphalt binder in the pavement adjacent to the crack resulting lower sealant adhesion (Masson and Lacasse 1999).

Sand blasting equipment consists of a compressed air unit, a sand blast machine, hoses and a wand with a venture-type nozzle which helps to ensure proper bonding by leaving a debris free cavity. But the disadvantage of sand blasting is that, it is more labor intensive compared with other cleaning and drying methods. Also, it often requires a second air compressor for follow up cleaning after the sand blasting operation (SHRP-H-348).

Wire brushing consists of a wire broom stock or stiff standard broom to brush out the crack which is quite effective at removing debris lodged in the crack reservoir. Generally high pressure air blasting and hot air blasting are used for crack sealing application. No studies evaluating the effectiveness of sand blasting and wire brushing were obtained during this literature review. The maximum distance between cleaning and sealing operations should be kept in between 60 to 80 feet.

Material preparation, application and installation

The selection of sealant mostly depends on the crack types and climate of the region. It is very important that the appropriate and best sealant material should be chosen for ensuring a successful sealing application. Also, it is the least expensive part of the job. According to the Nebraska Department of Roads Pavement Manual, "A value engineering study concluded 66% of total cost of crack sealing operation was for labor, 22% for equipment and 12% for materials". Eaton et al. (1992) suggested that the States with extensive freeze-thaw cycles need sealants with more ductility while warmer areas need sealants with less flow in hot weather.

Sealants are manufactured to meet many different federal, state, local, ASTM or AASHTO specifications. ASTM D6690 classifies four different types of sealants as follows:

Type 1: Crack sealant which is capable of maintaining an effective seal in moderate climates, with low temperature performance tested at -18^{o}C using 50% extension.

Type 2: Crack sealant capable of maintaining an effective seal in most climates, with low temperature performance tested at -29^{o}C using 50% extension.

Type 3: Crack sealant capable of maintaining an effective seal in most climates, with low temperature performance tested at -29^{o}C using 50% extension, and where special tests are also included.

Type 4: Crack sealant capable of maintaining an effective seal in very cold climates, with low temperature performance tested at -29^{o}C using 200% extension.

The two types of sealant most widely used are hot pour sealants and cold pour sealants. Hot pour sealant consists of asphalt cement with or without the addition of a modifier which must be heated to high temperatures in preparation for application. Rubber is the most common type of modifier which can increase the elasticity and melting point of the sealants. Hot pour sealants should be applied after cleaning the cracks and ensuring the pavement surface is free from moisture and dampness. Al-Qadi et al. (2009) recently developed an evaluation for standard methods and procedures on sealants called performance-based grading system for hot pour sealant based on fundamental material properties. The sealant materials identified sealant grade in the same way as Super Pave

PG asphalt binder grades. For example SG 76-16, where SG - Sealant Grade, 76 = the high temperature performance based on tracking resistance, °C; -16 = the low temperature performance based on stiffness, adhesion and cohesion properties, °C. Some modifications on rotational viscometer, vacuum oven aging, adhesion, direct tension and dynamic shear rheometer testing for sealant material are recommended.

Cold pour sealants do not require heating because they are applied at ambient temperatures. Emulsified asphalt material is the most commonly used type of cold pour sealant. The advantage of these sealants is that, it is more safe, as it does not require heating. Unlike hot pour sealant it can be applied when the cracks are moist or damp but it can have a high curing period. Yildirim et al. (2006) concluded that hot pour sealant has a better life cycle (3-5 years) compared to cold pour sealant (1-2 years). However the research study was conducted only for crack filling treatment.

Application of sealants

The application of sealants varies from State to State. According to SHRP-H-348 the selection of application of sealants depends upon the following facts:

1. Type of material
2. Size of job
3. Constraints on preparation time
4. Air temperature during preparation
5. Safety

The selection of material also determines the application method. Cold asphalt sealants are applied directly to the cracks where as hot pour sealant is melted in a double jacketed reservoir using heat transfer oil so that no direct flame comes in contact with the shell of the vessel containing the sealant (Yildirim et al. 2006). The melter must be capable of safely heating the sealant product to 400°F and heat transfer oil should not exceed 525°F (NCHRP Report 784 2014). According to ASTM D6690, hot pour sealants need to be agitated and heated, and maintained at the correct temperature throughout the application (Caltrans 2009). Figure 2-5 shows the hot pour crack sealant tank and its application.

Figure 2-5. Hot pour crack sealant tank and its application

The gauges measuring oil and sealant temperatures should be calibrated every spring (National Guide to Sustainable Municipal Infrastructure, 2003). Control of temperature is required in order to prevent sealant degradation (Masson et al. 1999). The melter should be equipped with a gear pump including insulated applicator hoses and wands connected to an adequate nozzle. Before the application of sealant to the pavement the application nozzle should be monitored according to manufacturer’s guidelines. Moisture must be cleaned so that bubbling should not occur during the time of application. After all preparation hot pour sealant should be applied to the pavement under cracks by a gear pump with a direct connecting applicator tip. A workday should begin with an empty melter without reheating the sealant. The overheating of sealant in order to get a rapid start up in the morning must also be avoided. (National Guide to Sustainable Municipal Infrastructure 2003).

Material finishes

The crack sealing application and material selection affects the finishing techniques. Generally squeegee is used for flush finishes and over banding methods during hot pour applications. Capped and recessed configurations do not need squeegee as these configuration intentionally left at a height above or below the driving surface. Also, there are various sizes of dish shaped attachments available which are connected to the end of the application wand for one step application and finishing (SHRP-H-348). Caltrans recommended that all sealant left on the surface shall be squeegeed flat in order to provide a smooth ride to the drivers.

Material blotting and curing

Blotting can be defined as the application of fine aggregate or sand to the non-cured sealant in order to prevent tracking (Yildirim et al. 2006). Clean and dry sand should be used to form a high quality blotter coat. Caltrans recommended that brooming should not be done over a blotter coat because it leaves broom marks and air voids in the sealant. Fine wood shavings can be used as a blotter coat because it is inexpensive, environmental and user friendly (National Guide to Sustainable Municipal Infrastructure 2003). Rolls of toilet paper or hygienic paper should be avoided because the motorist may confuse them with white pavement markings. Cement dust should not be used as it can affect the sealant properties, pollutes the air, and may burn the skin on repeated exposure. The road should not be reopened to traffic until the sealant has cured.

Crack Treatment Field Challenges

The sealant material should be selected carefully. On large projects, recommended testing should be performed on sealant materials. Overheating the material or heating the sealant material for prolonged period should be avoided. The solution is to monitor the temperature of the sealant in the melter and remove the material which has been heated for longer periods of time. Prolonged heating periods for hot applied material range between 6 & 12 hours (Murray 2013). Also, it is recommended that any material left in the melter at the end of the day should be removed and the melter should be thoroughly cleaned. Improper cleaning of a routed crack, over heating due to HAL while cleaning the crack, and damage to the pavement at the time of routing should be avoided. Crack sealing and filling treatment should be performed on younger pavements which are more susceptible to transverse and longitudinal cracking. For successful crack treatment, the working personnel need to understand the importance of the activities and the method of application. Although many agencies depend on-the-job-training (OJT) to learn these important methods, there is a lack of uniformity as the OJT is not performed completely or improperly due to the works needing to get done in a timely manner (production and profit). Contractors and municipalities are responsible for ensuring proper training among their respective personnel.

Quality Control

All precaution should be adopted and applied in order to extend the service life of pavement during the application of crack treatment. In order to extend the service life of pavement after the application of crack sealing all precaution should be adopted. According to the Guidelines for Sealing and Filling Cracks in Asphalt Concrete Pavement (2003) and Yildirim et al. (2006) following a quality control checklist should be maintained for successful crack treatment implementation. These checklists should include some or all of the following:

<u>Climatic Conditions</u>

Ambient temperature should be at least 40˚F and rising.

Make sure fog or dew is not present.

Early morning operations should be in direct sunlight.

<u>Routing</u>

Cutting tips should be sufficiently sharp to minimize spalling and cracking.

Appropriate safety clothes should be worn (hard hat, reflective vest, long-sleeved shirt, pants, steel toed boots, safety goggles and hearing protection.

Guards and safety mechanisms on equipment should be in place and work properly.

Router should follow cracks without difficulty.

Routs on asphalt concrete pavement should be free of spalling.

<u>Material Preparation</u>

Melter should be empty and no material should be reheated.

Heating oil in melter jacket should not fume and level should be adequate.

Temperature gauge on the melter should be calibrated within the last 6 months.

Overheating above the manufacture's recommended temperature should be prevented.

Safety data sheet (SDS) should be available on-site.

Cleaning of Cracks and Routs

A power sweeper or vacuum cleaner should be used to remove dirt and debris from the pavement surface.

Compressor for high pressure air should use at least 100 lb/in^2 of pressure.

Make sure oil and moisture filters on compressor work properly at least twice a day.

Temperature of the hot-air lance should be below 930°F and the tip should be placed 2 to 4 inches from the crack or rout.

The cleanliness of the crack or rout should be checked every 30 minutes.

Crack or rout should be free from moisture.

Sealant Application

Hot pour sealant should be poured at the manufacture's recommendation

The material should be applied to the inside of the cracks

There should be sufficient sealant to allow for a 1/5 to 2/5 inch band or bridge on either side of the crack

Moisture should be properly cleaned so that bubbles do not occur after the application of sealant

Sealant should be recirculated in the hose when installation train is idle.

Sealant Protection

Hot pour sealant surface should be covered with fine aggregate or sand without using broom. Traffic should not be opened until sealant is set.

Crack Treatment Performance and its Evaluation Criteria

Sealing of cracks is one of the most common maintenance activities due to its cost effectiveness and halting the deterioration of the pavement. Ponniah and Kennepohl (1996) stated that sealing cracks can decrease the rehabilitation cost and increase the service life of pavement. Chen et al. (2003) reported that sealing of cracks can be considered as the best alternative for the routine maintenance of sound underlying pavement structure. Several studies were carried out for selecting the appropriate sealant material, installation techniques and guidelines in order to achieve the best cost effective crack treatment.

Chong (1990) reported the performance and cost effectiveness of the feasibility of rout and seal treatment in flexible pavement based on the evaluation of three winter periods in Ontario. The study recommended specific routing configurations for different locations and confirmed that rout and seal operation can either delay or even stop the degradation of the pavement.

Smith and Romine (1993) organized a survey in which manufacturers and agencies were asked to put their comments regarding different aspects of crack treatment procedures such as desirable properties of cold and hot pour sealant materials, equipment application, safety and traffic control. Based on the results of survey they reported that the service life of hot pour sealant is 4.3 years and 2.2 years in warm and cold conditions, respectively. Life expectancy of cold pour sealant is 2.3 years and 1 year in warm dry and wet condition, respectively. In another study Smith and Romine (1993) also investigated the performance of 8 sealant configurations, 15 sealant materials and 7 crack preparation methods over a total 6705 m of cracks across US and Canada. After 7 years of monitoring period they found that rubberized asphalts installed in a shallow recessed band-aid configurations were the most cost-effective treatment.

Cuelho and Freeman (2004) conducted an evaluation of a combinations of 11 sealant materials and six sealing techniques in Montana. They monitored the performance of the crack treatment for four and a half years. They concluded that Crafco 522 with a shallow reservoir and flush or Crafco 231 with a square reservoir and flush was the most cost-effective crack treatment.

Fer and Kavanagh (2006) evaluated the performance of 9 hot-pour and 3 cold pour sealants based on a two year assessment of the sealant failure rate in Manitoba. They installed the hot pour and cold pour sealant in different configurations. It was found that hot pour sealant material outperformed the cold-applied sealants. Crafco Roadsaver 522 and Crafco Roadsaver 244 were permanently added to the Department's Products Standard List.

Masson et al. (1999) reported that hot pour sealant had a longer service life but more expensive than cold pour sealant. Also, Yildirim (2007) compared the field performance of hot pour and cold pour sealants in 5 different roads in 5 districts of Texas using crack filling technique. He found out that hot-pour sealants performed better than cold-pour sealants.

The performance life of a treatment mostly depends on the preparation of crack and the type of the material used (FHWA 1999). One inspection should be made each year to chart the rate of failure and plan for subsequent maintenance. A midwinter evaluation is highly recommended as it will indicate treatment effectiveness when there is maximum pavement contraction and the crack is near the maximum opening (FHWA 1999; SHRP-

H-348 1994). A small representative sample of the pavement, minimum of 150 m length should be selected for the evaluation. The following are common treatment failures which include-

1. Loss of full depth adhesion
2. Loss of full depth cohesion
3. Pull out of the sealant material
4. Spalling or the edge of crack break away as a result of poor routing or sawing
5. Potholes

According to FHWA (1999), the first step in determining a treatment's effectiveness is establishing how much of the treatment has failed in relation to the total length of treatment applied. Percent failure = (failed length after treatment/total length of treatment) x 100. After that the treatment's effectiveness can be determined by subtracting the percentage of treatment failure from 100 percent (Effectiveness = 100 - Percent failure). After a number of inspections a graph of effectiveness versus time can be developed.

Cost Effectiveness

Crack treatments can be considered as effective if it delays pavement deterioration and extends the pavement service life. Generally, the effective treatment extends the pavement life by two to five years (Evart et al. 1998; Chong 1990). According to Chong & Phang (1988) the effectiveness of rout and seal maintenance depends upon three points: (a) Performance of the sealant materials and appropriate rout width and depth; (b) restraining of crack development and delaying the existing pavement distress; and (c) crack treatment implication period. Eaton & Ashcraft (1992), stated that chip seal treatment cost 3-14 times more than crack sealing and an overlay cost 8-26 times as much as crack sealing. Also, Wang et al. (2012) concluded that sealing of cracks extend the pavement life approximately 1.7 years. Several studies have been performed in the US and abroad on different types of sealant materials and their performance evaluation criteria on these two types of crack treatments (Masson et al. 1999, Smith and Romine 1993 (a) (b), FHWA 1998). However, there is little or no comprehensive research on comparison of short and long term cost effectiveness between crack sealing and filling based on the real field cost data analysis.

Smith and Romine (1999) reported that the most cost effective treatment could be found with rubberized asphalt sealant materials that were placed in a shallow recessed band-aid configuration based on the seven-year performance monitoring of the various crack treatments.

Hand et al. (2000) conducted a literature review over 100 potential references regarding crack sealing. They found that only 18 of these references specifically address the cost effectiveness of crack sealing in terms of pavement performance and only four of the 18 consists of quantitative data. However, those studies were quite similar to each other and focused on the performance of material or technique combination rather than cost-effectiveness.

Masson et al. (2003) estimated the cost of installation and cost effectiveness for sealant materials with a hypothetical one to ten years of service life. They reported that crack filling would be more cost effective than crack sealing, if crack fillers were to show same durability. However, in their study they were assumed two different types of material for two treatment types, which includes: the use of hot-pour material for crack sealing and cold-pour emulsion for crack filling.

In another study, Cuelho et al. (2004) investigated the cost effectiveness of crack sealing materials and techniques for asphalt pavement. The study involved the use of eleven sealant materials with six sealing techniques in four experimental test sites. They have used the fourteen crack sealing bids over a six month period and eclectic forecasting model to estimate the cost of crack sealing. Also, the study did not consider the similar finishing technique for crack sealing and filling. They concluded that the use of Crafco 522 with a shallow reservoir and flush was the most cost-effective. They have also confirmed that after the fifth year evaluation, significant failures were observed for non-routed configurations (crack filling) compared to routed configurations (crack sealing).

Yildirim et al. (2006) investigated the field performance and compared the construction cost for hot and cold pour sealants. They have surveyed and studied thirty three different test sections in five districts using seven different sealant materials for four years. In their study they only consider crack filling treatment to treat the cracks. They concluded that hot pour sealants perform better than cold pour sealants and no significant difference in the construction cost.

The cost of crack treatment varies depending on state, materials, whether or not routing is required, and unit being priced. In Indiana in 2001, for example, the costs varied from twenty-four cents per linear foot to $1.33 per linear foot. The overall average cost per lane mile was $487.52, with a range from $302.57 to $713.48 (Ward, 2001). A student who knew about the industry indicated that the company they had firsthand knowledge of charged between fifty cents and $1.50 per linear foot for blowing out the cracks and sealing them. They charged between $1.25 and $2.25 per linear foot (total) if they were required to rout the cracks first. The price difference was dependent on quantity and if were other, “bigger ticket” items being performed the same job. The literature regarding the cost effectiveness of crack sealing and filling treatment is very limited.

Environmental Impacts

Transportation infrastructure in the United States is worth a trillion dollars which consists of over eight million lane-miles supporting three million vehicle-miles each year (Santero et al. 2009). In order to select the appropriate pavement maintenance activity importance should be implemented on the environmental aspects along with cost effectiveness. Several studies have been conducted on the cost effectiveness and performance of crack treatment methods (Hand et al. 2000, Masson et al. 2003, Cuelho et al. 2004). Few studies have been evaluated different pavement maintenance treatments in terms of energy and greenhouse gas (GHG) emissions.

Weiland and Muench (2010) used the life cycle assessment (LCA) approach to identify the environmental impact of three different rehabilitation techniques: 1) remove and replace the aging pavement with portland cement concrete (PCC) pavement, 2) remove the aging pavement and replace it with hot mix asphalt (HMA), and 3) crack and seat the existing pavement and place an HMA overlay. They reported that crack, seat and overlay option had the lowest energy consumption and global warming potential (GWP) whereas HMA option had the highest impact to the environment.

Chehovits and Galehouse (2010) estimated the energy use and GHG emissions of different pavement maintenance methods which are slurry seal, chip seal, HMA, hot in-place recycling, crack treatment, and fog seal. They concluded that chip seals, slurry seals, micro-surfacing, and crack treatment utilize the lower amount of energy and have less GHG emissions compared to overlay, rehabilitation and new construction practice. Other studies have studied the environmental impact due to different overlay systems (Zhang et al. 2008, Chappat and Billal 2003, Thenoux et al. 2008, Wang and Gangaram 2014). As it is evident from the literature that limited study has been done on the environmental impacts of crack filling and sealing treatments in terms of comprehensive initial and long term impact.

Analysis of Crack Treatment Practices in US

The literature review documented the different aspects of crack sealing and filling application and other factors which may impact the sealant performance. There is a very limited amount of literature considering the benefits of routing (crack sealing) over non-routing (crack filling) configuration in terms of cost effectiveness and its impact to the pavement performance. Further research and study is necessary for the better understanding of implementing a crack sealing treatment with routing configuration. It is a simple question:

Q: Is routing (crack sealing) hot mix asphalt pavement prior to installing crack sealant more cost effective than simply filling (crack filling) the cracks?

In order to examine the potential benefits of routing versus non-routing, the installation and in situ environmental factors must be monitored, and the material monitored over time and in varying temperatures. Based on field and maintenance plan simulation data, life cycle cost analysis (LCCA) must be performed, and the costs of the processes compared to see if there is a cost benefit to routing. In order to answer that question, survey have been conducted in a particular state where crack treatment is considered as one of the main pavement preservation technique. In Texas, crack treatment is one of the most used pavement maintenance program to mitigate the deterioration of new pavement. Current practice of crack sealing and filling treatment in Texas were analyzed by distributing survey questionnaires among the districts and found out the reason why the districts do not perform crack sealing treatment. Along with that the authors also summarized the crack sealing practices in other US states by through investigations on all state specifications.

Crack treatment practices in TxDOT districts

A survey of crack sealing and crack filling procedures was developed and distributed in Texas. The response was received and analyzed. Texas does not currently require routing, but decides on a case by case basis whether it is needed. Questionnaires were sent to 25 districts, response were received from 19. In Texas, no district practice routing however one of the responses (Amarillo) provided that they have routing practice in the past but leave it due to time consumption and equipment issue. Durability of crack sealant application varied from 3-5 years. However, 40 percent district do not have field evaluation for measuring the crack sealing performance. All those districts that responded, six of them stated that blowing out the debris from cracks with air has seemed to get them clean enough to seal and ensured good success with current method. Five districts responded that crack sealing with routing is a costly practice. Other districts mentioned that this practice is uncommon and do not have proper guidelines. Also, one district stated that they do not have any idea about its benefit. Responses to the questionnaire are provided in Table 2-6.

Table 2-6. Crack sealing practices within Texas

District	Does the district perform routing	If No – Why not	Durability of crack sealant application
Beaumont	No	Costly practice	3 years using hot pour
Paris	No	No guidelines	No evaluation performed
Yoakum	No	Uncommon practice	2-5 years
Tyler	No	Blowing out the debris from cracks with air has seemed to get them clean enough to seal	1 year
Corpus Christi	No	Costly	No evaluation performed
Pharr	No	No guidelines	2 years
Bryan	No	Good success with current method	No evaluation performed
Dallas	No	Compressed air ensure the adhesion and effectiveness	Typically 4 years
Lubbock	No	Costly practice	No evaluation performed
Odessa	No	Uncommon practice	No evaluation performed
San Angelo	No	Contractors are not equipped to provide this service and as a result, it would be very costly	4-5 years
Childress	No	Blowing out the debris from cracks with air has seemed to get them clean enough to seal	Average 2-3 years, but sometimes cracks need refilling the next year
Laredo	No	Uncommon practice and have had good success with current method	No evaluation performed
Amarillo	No	Routing practice in the past but leave it due to time consumption and equipment issue	3-5 years using hot pour
Waco	No	Blowing out the debris from cracks with air has seemed to get them clean enough to seal	No evaluation performed
Lufkin	No	Typically blow the debris from crack with air and fill the crack with sealant	1-2 years
Fort Worth	No	Hot pour crack seal has been used in the district to penetrate the crack width without routing	No evaluation performed
Austin	No	Not cost effective	3 years
Brownwood	No	Insufficient knowledge about benefits	5-10 years

Decker (2014) conducted a survey on 157 individual represents 28 state DOTs, 106 countries, 3 cities, 2 Federal Highway Administration (FHWA), 1 Canadian province, 2

U.S. contractors and 1 contractor from New Zealand. They were asked to estimate the typical life span for crack sealing and crack filling on both major and minor roads. They concluded that majority of the respondents think crack sealing on both major and minor roads can perform for 5-10 years, but that crack filling will only last 1-4 years. Yildirim et al. (2006) reported that crack sealing without routing configuration using hot-pour sealant materials have a typical life cycle of 3-5 years. Rajagopal (2011) reported that their prediction model indicated a life span of 3.6 years for crack filling treatment. According to literature review and survey from the Texas districts, the research team considered the pavement could stand with crack filling for 3 years and crack sealing for 5 years.

Out of province practices

In order to get an overall view on crack sealing practice, investigations on all state specifications has been performed. Among all those States of USA, 20 States specifically mention routing in flexible pavement. Indiana has a specific item and substantial published cost information for the last 12 months.

A map has been made based upon the routing practices in the different states. Figure 2-6 illustrates the map where States with routing practice included in crack seal specifications.

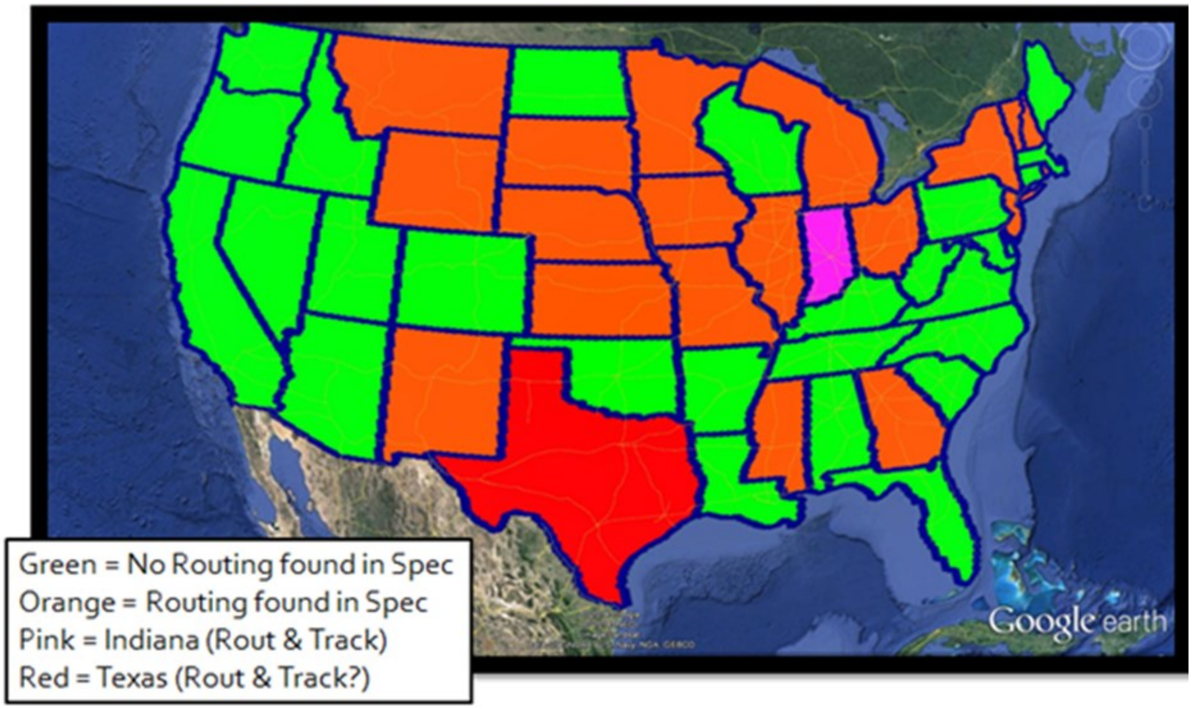


Figure 2-6. States with routing practice

This chapter (II) includes a part of the following publications;

Mazumder, M., Kim, H. H., Lee, M.S., Lee, S.-J., "A review on Different Aspects of Crack Treatment Methods" *to be submitted to Innovative Infrastructure Solutions.*

CHAPTER III

STATISTICAL ANALYSIS METHOD

A statistical analysis was performed using the IBM SPSS program and Microsoft Excel to conduct an analysis of variance (ANOVA) and Fisher's Least Significant Difference (LSD) comparison with an $\alpha = 0.05$. The statistical design was based on conducting rotational viscosity tests, dynamic shear rheometer (DSR), and bending beam rheometer (BBR) test of different SIS contents.

The ANOVA was performed first to determine whether significant differences among the sample means existed. In the analyses of this study, the significance level was .95 ($\alpha = 0.05$), indicating that each finding had a 95% chance of being true. The calculations for ANOVA analysis were performed using the one way ANOVA in IBM SPSS. The ANOVA table is shown in Table 3-1. The hypotheses for these tests are as follows:

H_0: Mean viscosity values for all SIS contents are equal

(i.e., $\mu_1 = \mu_2 = \mu_3 = \ldots = \mu_a$)

H_1: at least one $\mu_i \neq \mu_j$

If H_0 is rejected at the 5% confidence level, the LSD test is used to identify which treatments are different. Upon determining that there were differences among sample means using the ANOVA, the LSD was then calculated. The LSD is defined as the observed differences between two sample means necessary to declare the corresponding population means difference. Once the LSD was calculated, all pairs of sample means were compared. If the difference between two sample means was greater than or equal to the LSD, the population means were declared to be statistically different (Ott 2001).

Table 3-1. Analysis of Variance (ANOVA) Table

Source	*Sum of squares*	*Degrees of freedom*	*Mean square*	F_0
Treatments	$SS_{Treatments}$	a-1	$SS_{Treatments}$/(a-1)	MS_T/MS_E
Error	SS_E	N-a	SS_E/(N-a)	
Total	SS_T	N-1		

Where,

$SS_{Treatments}$= treatment sum of squares in between

SS_E = sum of squares for error

SS_T = sum of squares for total

CHAPTER IV

PHYSICAL, RHEOLOGY AND MICROSTRUCTURAL PROPERTIES

Introduction

Crack sealant material should have high stiffness property in order to prolong the life of the pavement resulting the saving of the transportation agency. Styrene-Isoprene-Styrene (SIS) polymer has higher aging resistance, good blend stability, and improve elastic response, superior cohesion, tensile strength and low-temperature flexibility. As a result, it is expected that SIS polymer has the potential to become a crack sealant product by blending it with asphalt material due to its high stiffness and elasticity.

In this chapter, control PG 64-22 is modified with five different percentages of SIS content (0%, 5%, 10%, 15%, and 20%). Viscosity change as a function of SIS amount is evaluated through rotational viscometer (RV) test using two testing temperatures (135°C and 180°C). Dynamic shear rheometer (DSR) and bending beam rheometer (BBR) were used to investigate high temperature and low temperature rheological behavior of asphalt binder modified with SIS. Microstructural properties of SIS modified binder were investigated using atomic force microscopy (AFM) and environmental scanning electron microscopy (ESEM). Also, absorption and reflection index of the binder is observed using ellipsometry. Figure 4-1 shows a flow chart of the experimental design used in this study.

Figure 4-1. Flow chart of experimental design.

Experimental Program

Materials

Performance grade (PG) 64-22 asphalt binder as a base binder was used in this study. The SIS modifier included in this study was obtained from one source. It is a blend of linear SIS triblock and SI diblock copolymer. It contains approximately 18% SI diblock copolymer. Figure 4-2 and Table 4-1 show the image and properties of SIS modifier.

Figure 4-2. SIS modifier

Table 4-1: Properties of SIS modifier

Properties	Test Method	Units	Typical Value
Styrene	TSRC/DEXO Method	wt%	15
Diblock content	TSRC/DEXO Method	wt%	18
Melt Flow Rate (200°C/5kg)	ASTM D1238	g/10 min	11
Solution viscosity	ASTM D2196	cps	1240
Ash	ASTM D5630	wt%	0.3
Tensile strength	TSRC/DEXO Method	MPa	25
300% modulus	TSRC/DEXO Method	MPa	1.1
Elongation	TSRC/DEXO Method	%	1250
Hardness	ASTM D2240	Shore A	33
Bulk density	ASTM D1895	g/cm^3	0.55 (4113A)
Specific gravity	ASTM D792		0.92

There are two ways to mix the binder: wet process and dry process. In general, the wet process is used for laboratory experiments. The reason is that the wet process is easier to manage the binder quality than the dry process. Therefore, the binder mixing was used in this study is the wet process. In the wet process, the SIS modifier is added to the base asphalt binder (PG 64-22). The SIS binder is produced in the laboratory at 180 °C for approximately one and half hours by an open blade mixer at a blending speed of 700rpm. Five percentage content (0, 5, 10, 15 and 20%) of SIS modifier are used to make the SIS binder.

<u>Rotational viscosity (RV) test</u>

A Brookfield rotational viscometer is utilized to determine the viscosity of SIS binder at 135°C and 180°C per AASHTO T 316. The viscosity is determined by measuring the torque required to maintain a constant rotational speed of a cylindrical spindle while submerged in an asphalt binder sample at a constant temperature. A 10.5g binder sample is tested with a number 27 cylindrical spindle (10.5 mL) rotated with constant speed (20 rpm) for SIS binder. The control binder is tested in accordance with the same procedure except an 8.5g sample using a number 21 spindle (8mL). Testing period of 30 minute is used to evaluate the viscosity change in different testing periods. According to the Superpave binder test, the maximum viscosity of unaged asphalt binder is 3.0 Pa-s (3000 cP). Figure 4-3 shows a picture of a rotational viscometer.

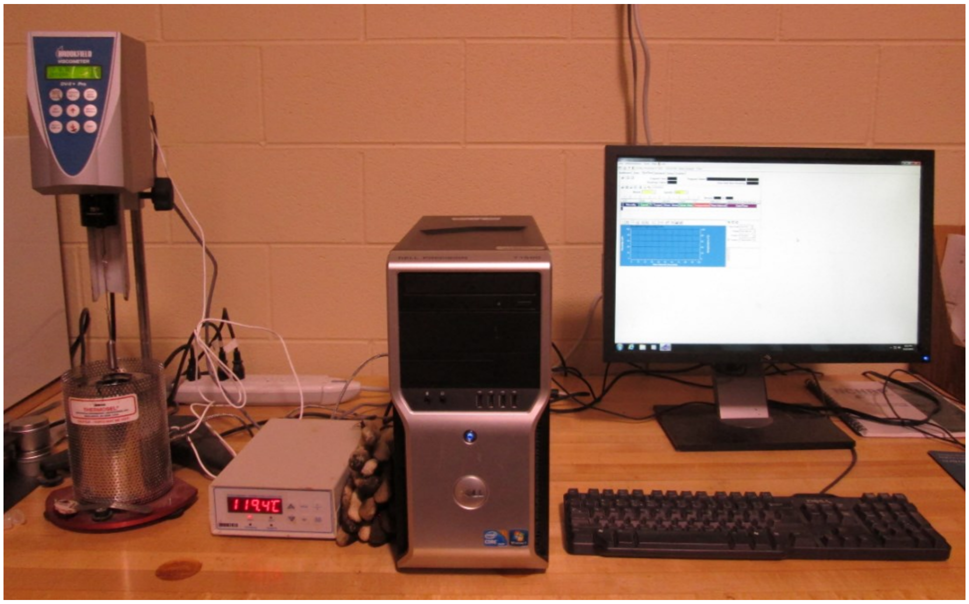


Figure 4-3. Rotational viscometer

Dynamic Shear Rheometer (DSR) Test

The high temperature rheological properties of SIS binders are measured using a dynamic shear rheometer (DSR) per AASHTO T 315. In the DSR test, the original binder is tested with 25 mm spindle at 82°C and parallel plate and also tested using an 8 mm parallel plate at 25°C. Figure 4-4 shows a DSR testing apparatus used in this study. In the DSR test, the binders are tested at a frequency of 10 radians per second which is equal to approximately 1.59 Hz. Each asphalt binder is tested to determine the G*/sin δ. The G*sin δ at intermediate temperature is measured to evaluate the fatigue cracking property of the binders.

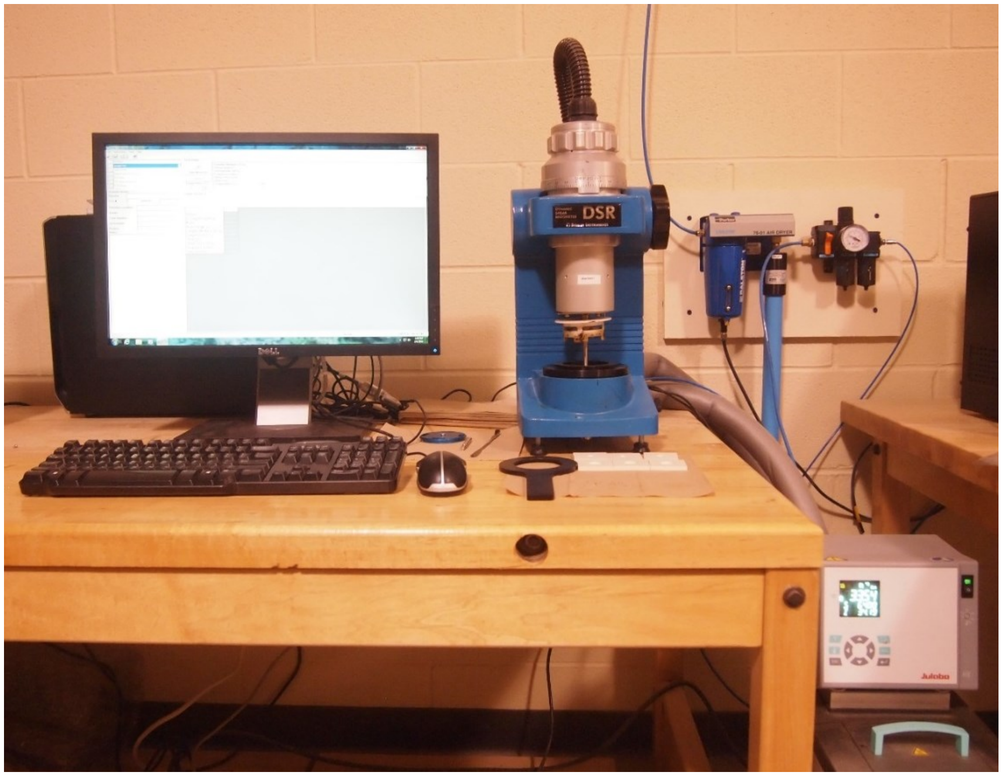


Figure 4-4. Dynamic Shear Rheometer (DSR)

Bending Beam Rheometer (BBR) Test

BBR test is used to evaluate cracking property at low temperature. The stiffness is measured at -24°C. Figure 4-5 shows a BBR testing apparatus. The BBR test is conducted on asphalt beams (125 × 6.35 × 12.7 mm) at -24°C, and the creep stiffness (S) of the binder measured at a loading time of 60s. A constant load of 100g is then applied to the beam of the binder, which is supported at both ends, and the deflection of center point is measured continuously.

Figure 4-5. Bending Beam Rheometer (BBR)

Atomic Force Microscopy (AFM)

A Model 840-002-380 Bruker Dimension Icon AFM (Bruker Instrument Inc.) is used to characterize the micromorphology of SIS binders through the surface images obtained on prepared sample. Topographical and phase images are captured. Figure 4-6 shows the AFM equipment.

AFM can be used to measure the forces between the tip and the sample as a function of their mutual separation. The AFM tapping mode imaging is performed on the binder samples to evaluate the morphology of the binder. In the tapping mode, the AFM tip is oscillated at its resonance frequency by a piezoelectric element connected to the tip holder assembly. The piezo-drive is adjusted using feedback control to maintain a constant tip-up-sample distance (set point) (Bhushan and Qi 2003).

Both height and phase images are obtained with the scan rate of 0.99Hz and the scan size of 20μm × 20μm. Height images represent the topography of the surface. Phase images are displayed for the unambiguous resolution which can be hindered by surface roughness in topographic image captured by the height mode in AFM. The colors in the phase images designate different mechanical properties of the phases, as obtained from sample–tip interactions, and could be related to their different viscoelastic properties or adhesion.

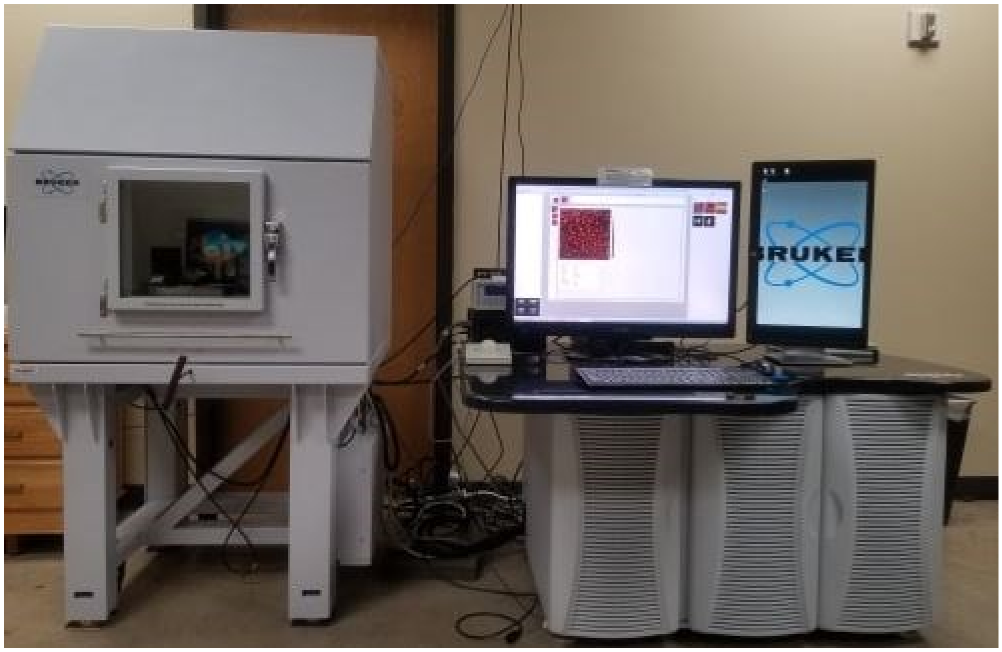


Figure 4-6. Atomic Force Microscopy (AFM)

Environmental Electron Scanning Microscopy (ESEM)

To image wet, soft and non-conducting samples with scanning electrons, a technique called environmental SEM or ESEM was developed by G. Danilatos in mid-eighties (Danilatos 1990). The term ‘environment’ stems from the idea that this technique allows imaging of samples by varying the sample environment through a range of pressures, temperatures and gas compositions. ESEM provides all of the performance advantages of a conventional SEM, but removes the high vacuum constraint on the sample environment. In ESEM, wet, oily, dirty, non-conductive samples can be examined in their natural state without any damage to surface or surface preparation (Donald et al. 2003). ESEM provides high resolution scanning secondary electron imaging in almost any gaseous environment at pressure as high as 50Torr and temperature as high as 1500 ^{o}C (Donald et al. 2003). Therefore, electron imaging of asphalt can only be performed in ESEM without any concerns of surface damage and conductive coating. In this study JEOL (Model #: JSM-6010PLUS/LA) ESEM is used to examine the surface microstructure of SIS binder. The degree of magnification is chosen to be 1000X. The scan sizes used are 10μm. The equipment settings used for scanning are as follows, 5-10kV; pressure, 40Pa. Figure 4-7 shows the JEOL ESEM.

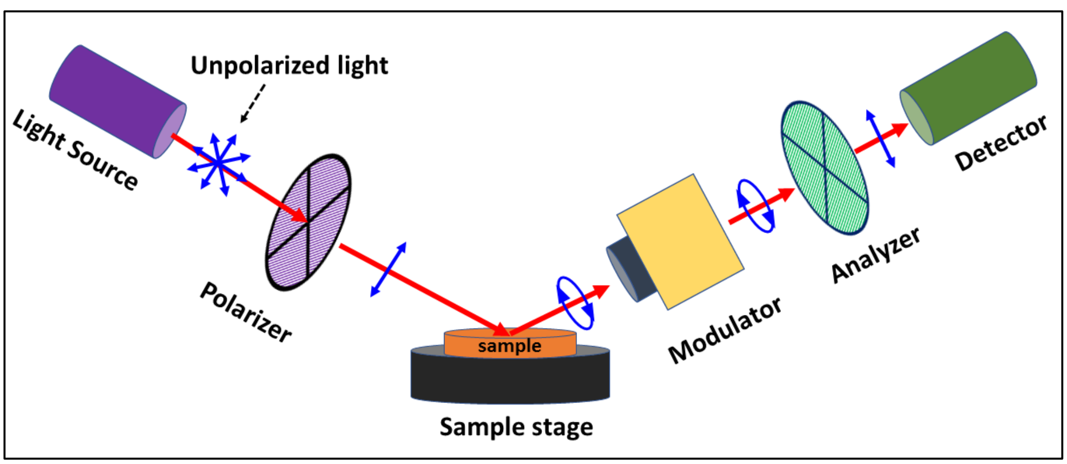
Figure 4-7. Environmental Electron Scanning Microscopy (ESEM)

Ellipsometry

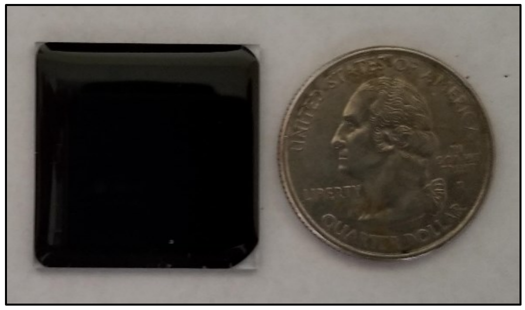
The interaction of light with any material surface is characterized by complex refractive index of material which comprises a real (refractive index) and imaginary part (extinction or absorption coefficient) (Tompkins and McGahan 1999). Spectroscopic ellipsometry is a powerful tool for determining both refractive index (n) and extinction coefficient (k) of any thin film. More specifically, ellipsometry involves measurement of the change of state of polarization for light reflected at an oblique angle from the surface of a sample (Tompkins and McGahan 1999). The polarization change results in change in phase and these changes are analyzed with appropriate algorithms based on various optical parameters to obtain film thickness, refractive index (n) and optical loss (k) (Woollam et al. 1999). The complex refractive index is given by (Kittel et al. 1976),

$$n\ (\lambda) = n - ik \text{............(1)}$$

The real part of the refractive index (n) describes how the speed of light changes as it enters the material and the extinction coefficient (k) describes how light is absorbed or scattered (Elton 2007).



(a)



(b)

Figure 4-8. Ellipsometry (a) Schematic diagram of spectroscopic ellipsometry system and (b) prepared sample

Spectroscopic ellipsometry is mainly used for analyzing thin films, thin films of asphalt binders are made on glass substrate (20mm × 20mm) as shown in Figure 4-8. A sample is prepared by pouring melted binder on the surface of a glass substrate. All binders are preconditioned by controlled heating at 170°C in an oven for 10 minutes and then a drop (~10 mL) of liquid asphalt is poured on the glass substrate. Variable angle spectroscopic ellipsometry (VASE) data are collected in reflectivity mode using a J.A Woollam (model M 2000 UI) Ellipsometer. Variable angle spectroscopic data are collected in the wavelength range of 290 nm -1690 nm in three different angles, 55°, 60° and 65°. A model is created and measured data are fitted with the model generated spectra to obtain optical constants, n and k. The ultimate goal of this step is to achieve least mean square error (MSE) between the model generated spectra and the actual spectra which would result in true optical constant for the layer material. As the optical properties of the asphalt binders are unknown, a simple model of glass with absorbing film is used at first. Later, the model is chosen as a Cauchy model for glass and B-spline model for the asphalt and a global fit is performed (Jenkins and White 1937). For each of the films the mean square error is less than 1. Optical constants for the entire measurement wavelength range is then plotted for SIS binders.

Results and Discussions

Viscosity property

The viscosity of asphalt binder at high temperature is considered to be an important property to decide working temperature because it reflects the binder's ability to be pumped through an asphalt plant, thoroughly coat aggregate in a HMA mixture, and be placed and compacted to form a new pavement surface (Asphalt Institute 2003). Figure 4-9 shows the standard RV test results for SIS binders at 135°C and 180°C. It is evident that the addition of SIS into the asphalt binder increases the binder viscosity for both testing temperatures. The viscosity of 15% and 20% SIS binder could not be measured at 135°C. The viscosity values of PG 64-22, SIS 5% and SIS 10% at 135°C are found to be 635 cP, 2028 cP and 7008 cP, respectively. It is worth to note that the viscosity of SIS binder seems to have insignificant change after adding more than 15% of SIS content.

The statistical significance of the change in the viscosity as a function of SIS content is examined and the results are shown in Table 4-2. At 135°C, the difference among all the SIS binders is found to have statistically significant. The difference between 15% SIS and 20% SIS binder is observed to be statistically insignificant at 180°C.

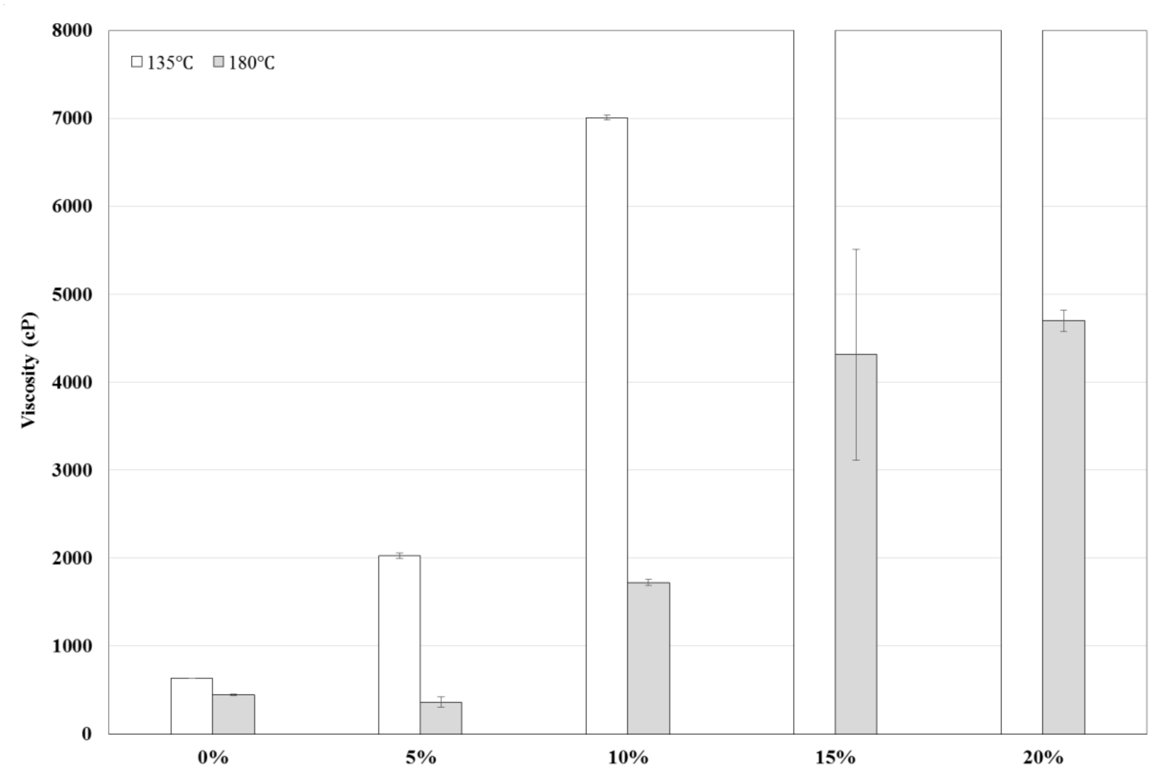


Figure 4-9. Viscosity of SIS binders at 135°C and 180°C

Table 4-2. Statistical analysis results of the viscosity value as a function of SIS content; (a) 135°C and (b) 180°C

(a)

Viscosity	SIS 0%	SIS 5%	SIS 10%	SIS 15%	SIS 20%
SIS 0%	-	S	S	S	S
SIS 5%		-	S	S	S
SIS 10%			-	S	S
SIS 15%				-	S
SIS 20%					-

(b)

Viscosity	SIS 0%	SIS 5%	SIS 10%	SIS 15%	SIS 20%
SIS 0%	-	N	S	S	S
SIS 5%		-	S	S	S
SIS 10%			-	S	S
SIS 15%				-	N
SIS 20%					-

N: non-significant S: significant

Rutting Property

The higher G*/sin δ values from the DSR test indicate that the binders are less susceptible to rutting or permanent deformation at high pavement temperature (Asphalt Institute 2003). The G*/sin δ values of unaged SIS binders at 82°C are shown in Figure 4-10. It is evident from the figure that the addition of SIS modifier significantly increases the rutting resistance of the binder. It means that the SIS has a positive effect on the rutting resistance at high temperature which causes an increase in the complex modulus of the binders. However, the percentage improvement of rutting resistance after 15% addition of SIS modifier is found to be less significant. Table 4-3 presents the statistical significance of the change in the G*/sin δ as a function of SIS content. In general, the data indicat that SIS content has significant effect on G*/sin δ.

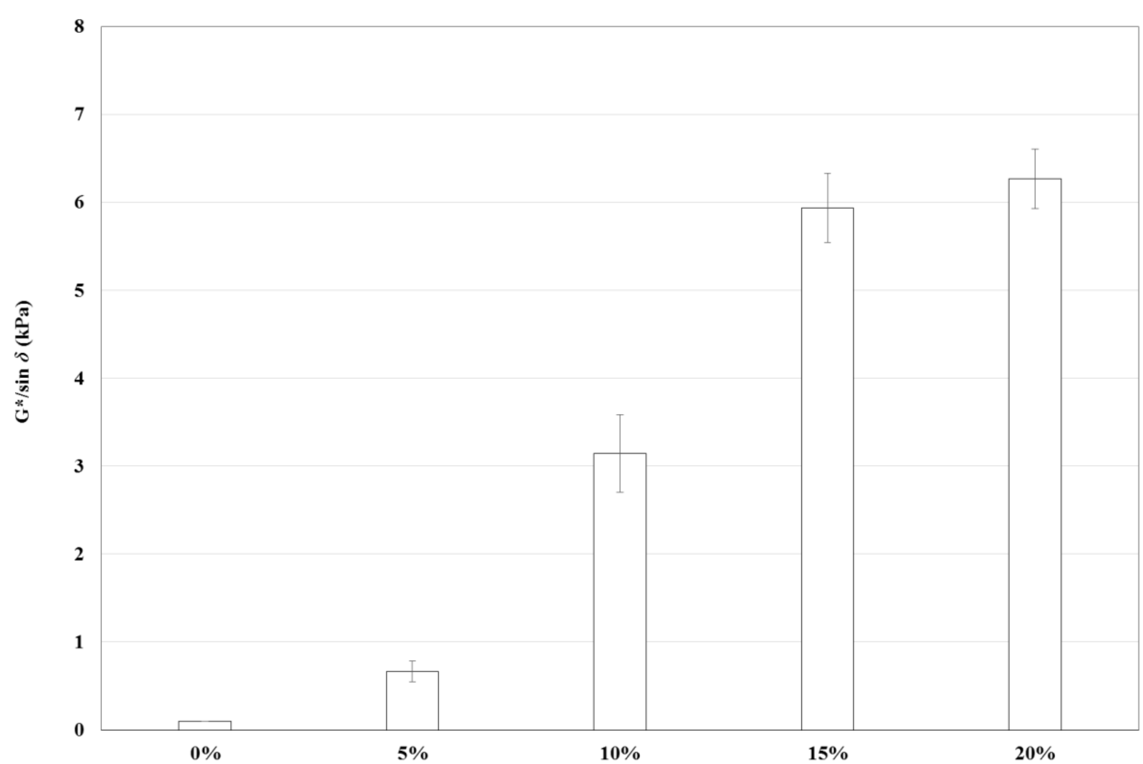


Figure 4-10. G*/sin δ of SIS binders at 82°C

Table 4-3. Statistical analysis results of the G*/sin δ value as a function of SIS content

G*/sin δ	SIS 0%	SIS 5%	SIS 10%	SIS 15%	SIS 20%
SIS 0%	-	S	S	S	S
SIS 5%		-	S	S	S
SIS 10%			-	S	S
SIS 15%				-	N
SIS 20%					-

N: non-significant S: significant

Cracking Property

Fatigue cracking property

In general, the lower G*sin δ values are considered to be desirable attributes from the standpoint of fatigue cracking resistance (The Asphalt Institute 2003). The G*sin δ values of the SIS binders are determined using the DSR at 25 °C and the results are illustrated in Figure 4-11. The G*sin δ values are found to be 1210, 1101, 146, 140 and 97 kPa for the binders of control (PG 64-22), SIS 5% (PG 64-22 + 5% SIS), SIS 10% (PG 64-22 + 10% SIS), SIS 15% (PG 64-22 + 15% SIS) and SIS 20% (PG 64-22 + 20% SIS), respectively. With the increase of SIS percentage the binder is found to have more cracking resistance.

Using one-way ANOVA, the statistical significance of the change in the G*sin δ values is examined and shown in Table 4-4. The data indicate that the SIS content has a significant effect on the G*sin δ values. Meanwhile, the difference among the binders of SIS 10%, SIS 15% and SIS 20% is found to be statistically insignificant.

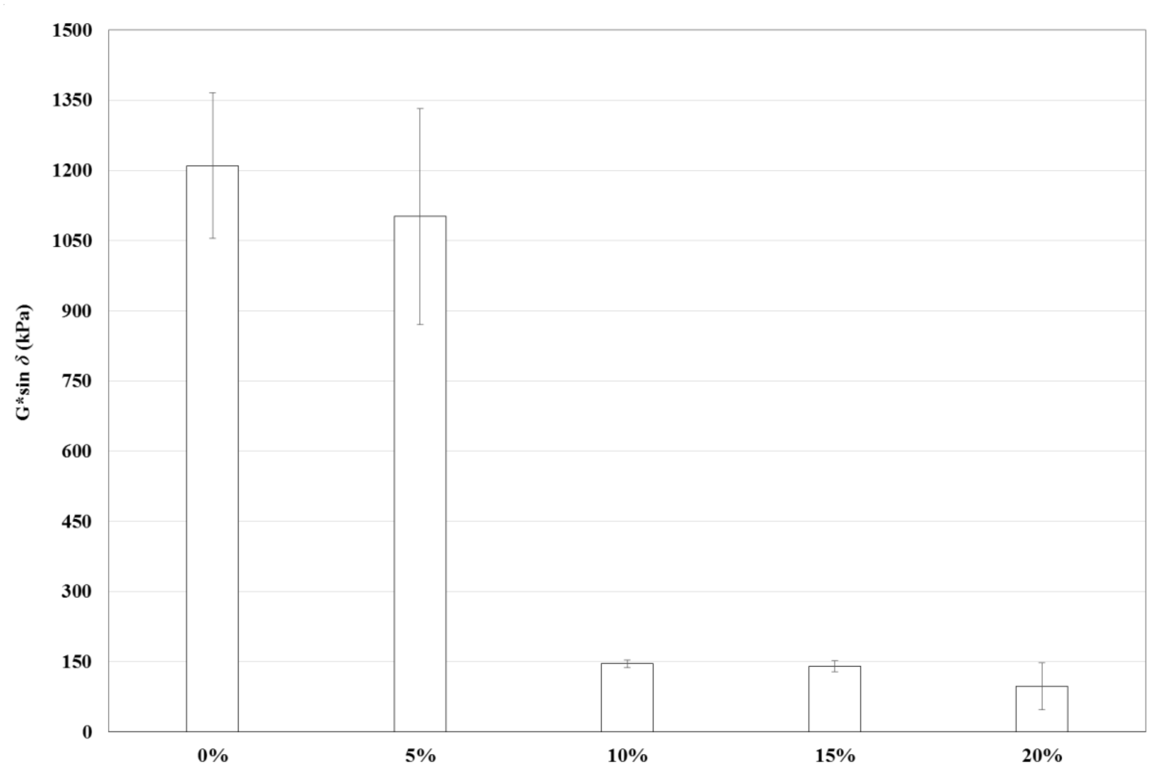


Figure 4-11. G*sin δ of SIS binders at 25°C

Table 4-4. Statistical analysis results of the G*sin δ value as a function of SIS content

G*sin δ	SIS 0%	SIS 5%	SIS 10%	SIS 15%	SIS 20%
SIS 0%	-	N	S	S	S
SIS 5%		-	S	S	S
SIS 10%			-	N	N
SIS 15%				-	N
SIS 20%					-

N: non-significant S: significant

Stiffness

From the BBR tests at -24°C, the stiffness and *m*-value of SIS binders at original state are calculated and results are illustrated in Figures 4-12 and 4-13, respectively. It is found that the addition of SIS into the asphalt binder significantly decreases the low temperature stiffness. The addition of 5% SIS and 10% SIS resulted in decreasing the stiffness of control PG 64-22 binder by 26% and 51%, respectively. Also, with the percentage of SIS modifier increased, the low temperature stiffness of the binder is observed to be decreased.

The one-way ANOVA is conducted to investigate the statistical change in the stiffness as function of SIS content and the results are summarized in Table 4-5. The binder with 10% SIS is statistically significant compared to the binders with SIS 15% and SIS 20%. On the other hand, the difference between SIS 15% and SIS 20% is statistically insignificant at the 5% level.

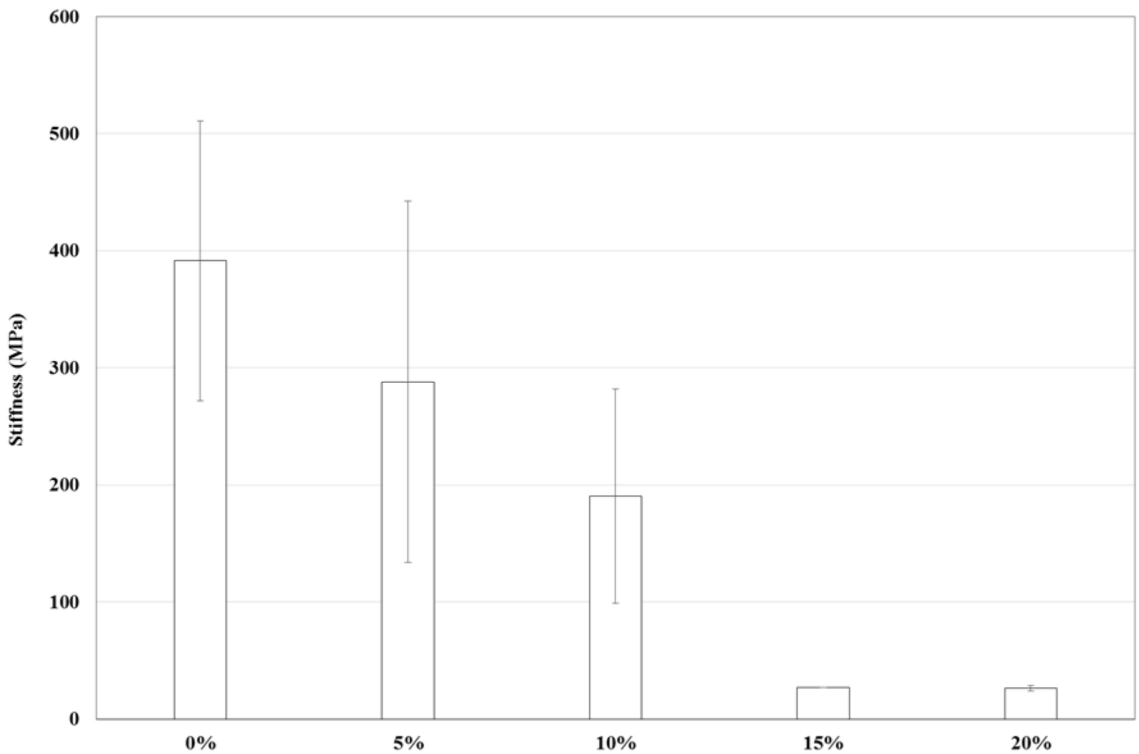


Figure 4-12. Stiffness of SIS binders at -24°C

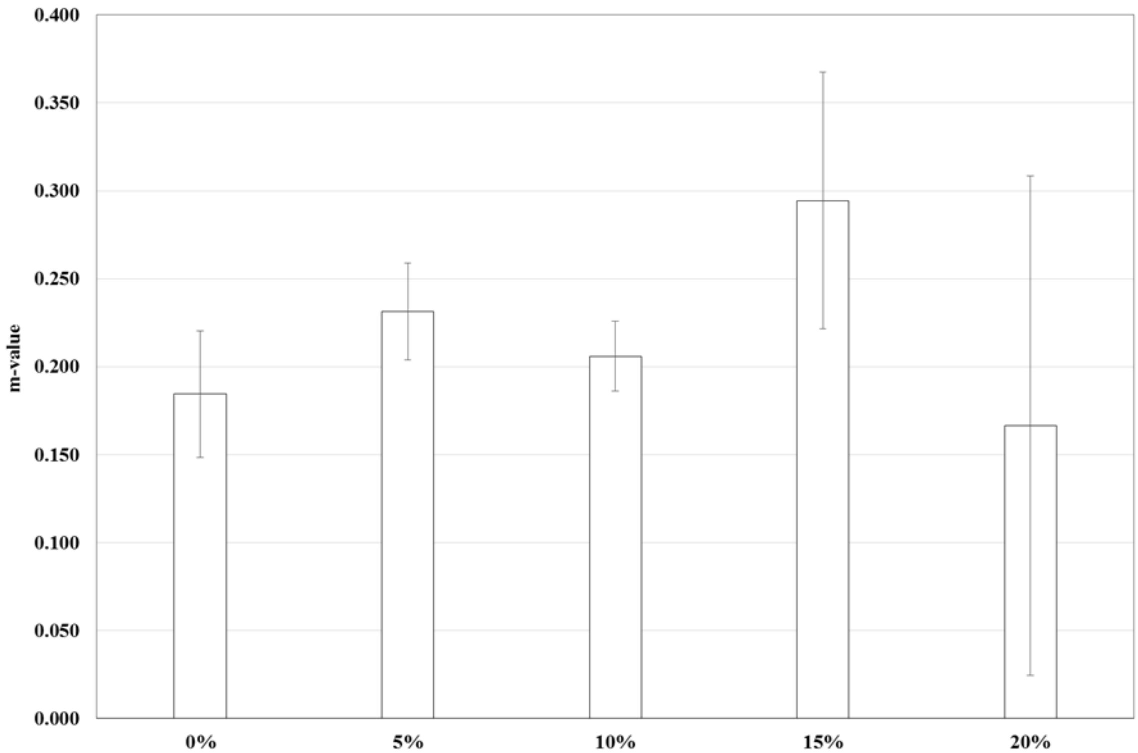


Figure 4-13. m-value of SIS binders at -24°C

Table 4-5. Statistical analysis results of the stiffness value as a function of SIS content

Stiffness	SIS 0%	SIS 5%	SIS 10%	SIS 15%	SIS 20%
SIS 0%	-	N	S	S	S
SIS 5%		-	N	S	S
SIS 10%			-	S	S
SIS 15%				-	N
SIS 20%					-

N: non-significant S: significant

Microscopy Property

AFM images

Figure 4-14 shows the topographic and phase images of unaged PG 64-22 at a scan size of 20 µm after 24 h. The topographic image consists of a microstructure which looks like a sequence of hills and valleys. This distinct feature is known as bee-like structure and it is more evident in the phase image (Pauli et al. 2011). The phase image consists of three different features which are: the catana phase (bee-like structure), the peri phase (the area surrounding the bee structure) and the para phase (the red solvent region). The catana and peri phase constitutes the dispersed domains which is responsible for the stiffness of the binder (Kim et al. 2017). It has more stiffness compared to the para phase or matrix. It can be observed from the topography image that the control binder has increased size of bee structure which are embedded on the surface in an organized way. The phase image gives more insight of the dispersion of dispersed domains and the matrix of the binder. It is clearly evident that the control binder consists of large area of dispersed domains compared to the matrix.

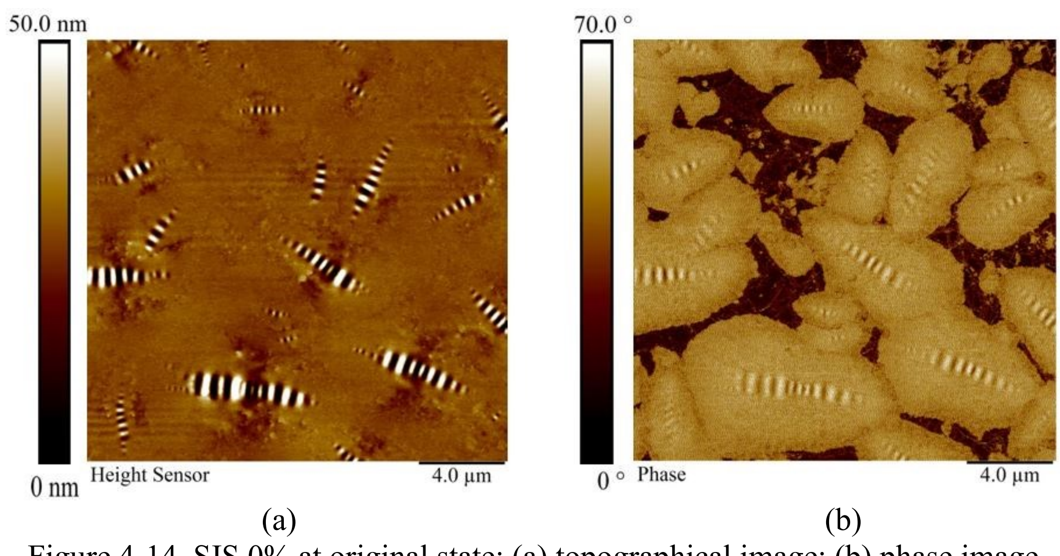
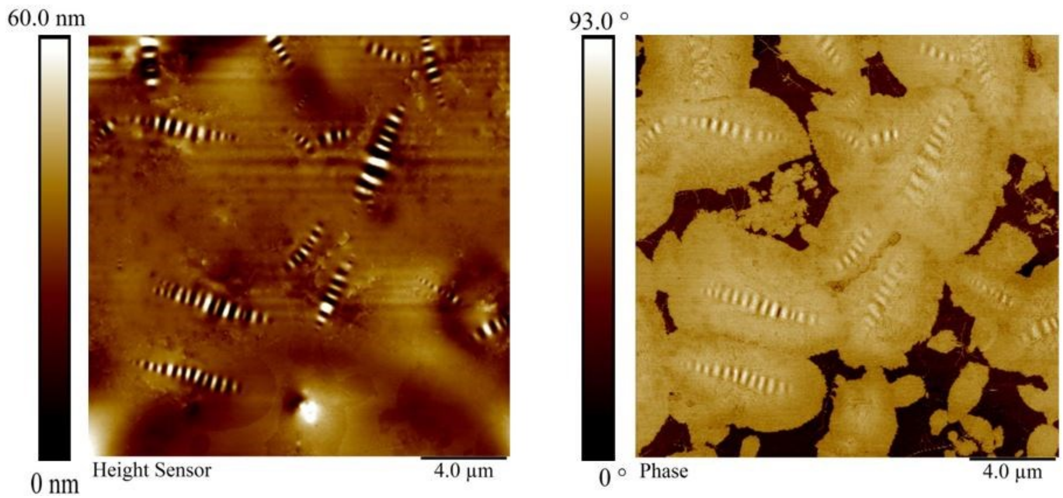


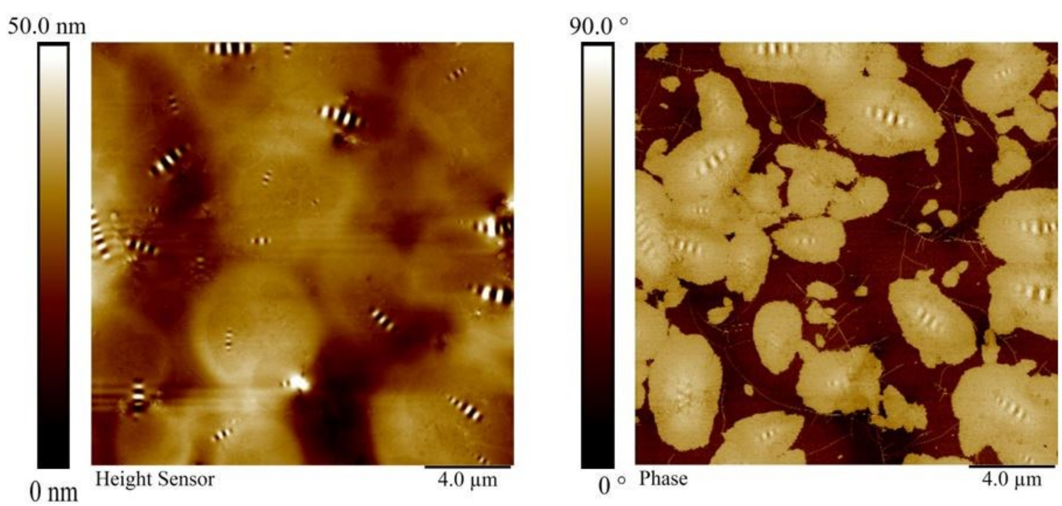
Figure 4-14. SIS 0% at original state: (a) topographical image; (b) phase image

Figure 4-15 presents the topographic and phase image of the binder with 5% SIS modifier. In the topographic image, the number of bee structure is reduced and it is more evident in phase image. From the previous studies (Kim et al. 2017) it is found that microcrystalline waxes and waxy molecules are responsible for the bee structures. The addition of SIS modifier might dissolve the waxy molecules which contributes to the disappearance of the bee-like structures and make it less stiff compared to the control binder (Zhang et al. 2011).



(a) (b)

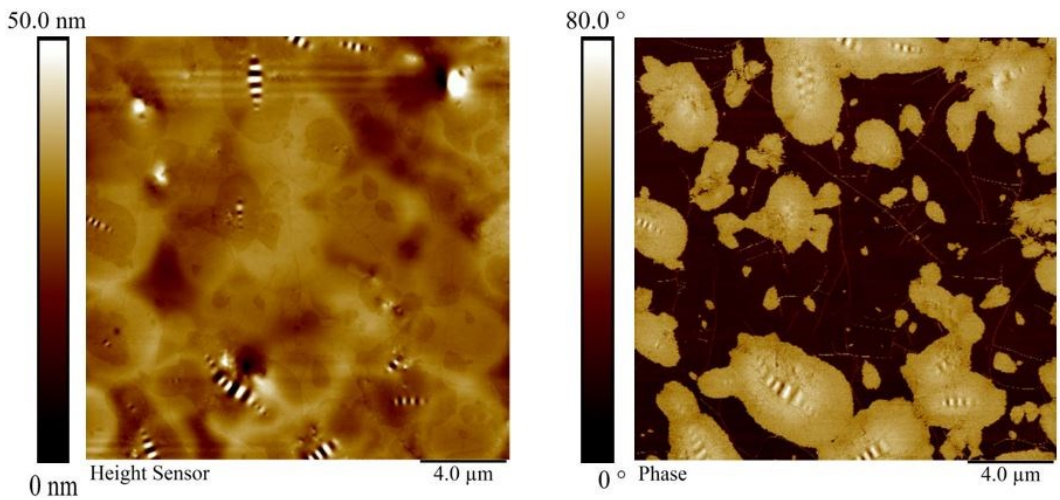
Figure 4-15. SIS 5% at original state: (a) topographical image (b) phase image



(a) (b)

Figure 4-16. SIS 10% at original state: (a) topographical image; (b) phase image

Figure 4-16 (a and b) illustrates the topographic and phase image of the binder containing 10% SIS modifier. The addition of further amount of SIS modifier decreased the size and width of the bee structure (Figure 4-16 (a)). However, a new phase which is an oval shape is observed to evolve in topography image. On the other hand, in the phase image the area of matrix phase significantly increases and the peri phase surrounding bee structure also gets reduced.

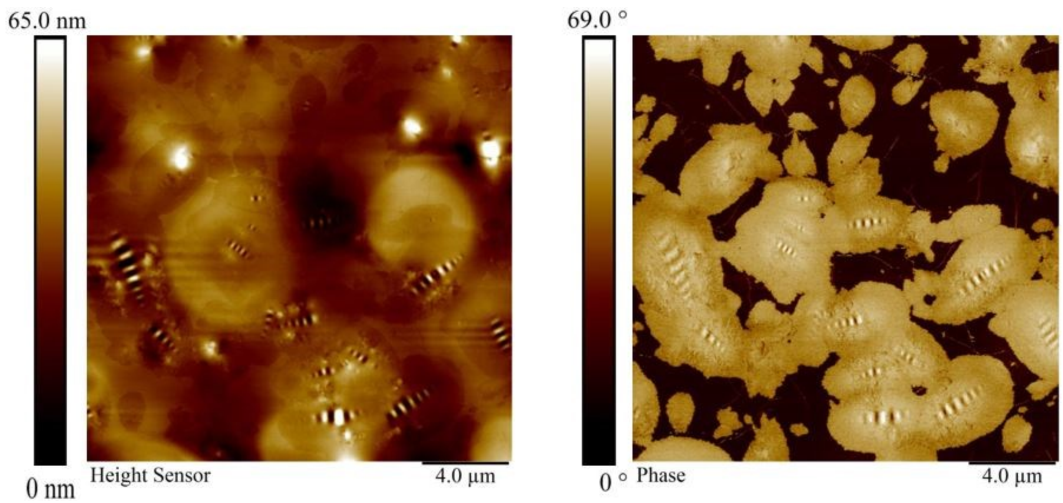


(a) (b)

Figure 4-17. SIS 15% at original state: (a) topographical image; (b) phase image

AFM images in Figure 4-17 (a and b) show the further addition of SIS modifier (15% of the binder weight) reduced the size and number of bee structures. The new phase identified in Figure 4-17 (a), the oval shape appears to be brighter for this binder type. The area of dispersed domain is reduced significantly and the para phase or the solvent region cover most of the area of the phase image. It indicates that the addition of SIS modifier has a significant effect on the micromorphology of PG 64-22.

Figure 4-18 (a and b) presents the topographic and phase image of binder with 20% of SIS modifier. The trend is consistent with the earlier findings as the number of bee structures appears to be less in the topographic image. However, there is no significant distinction between the binders with 15% and 20%. Also, difference between the rheological data of these two binders are observed to have non-significant. The new oval phase is observed to have increased in size. Although the peri phase is found to be expanded compared to Figure 4-17 (b), the number of bee structures appeared to be consistent.



(a) (b)

Figure 4-18. SIS 20% at original state: (a) topographical image; (b) phase image

The aforementioned discussions of microstructural properties of the binder modified with SIS modifier are found to be consistent with the stiffness properties of the binder. Among all the binder types the control binder has the highest stiffness and as the amount of SIS modifier increases, the binder becomes less stiff based on the difference of contrast between dispersed domains and matrix.

ESEM images

ESEM images are captured for the SIS binder at original state. Figure 4-19 shows ESEM image of control PG 64-22 binder. The formation of three dimensional entangled network structure has been observed after several minutes of beam exposure in ESEM. The fibrils of the network structure are consisting of high molecular weight asphaltene/resin micelles and contributes significantly to the fracture behavior of asphalt binder (Rozeveld et al. 1997). It can be observed that the fibril structures are relatively denser and thicker for the control binder.

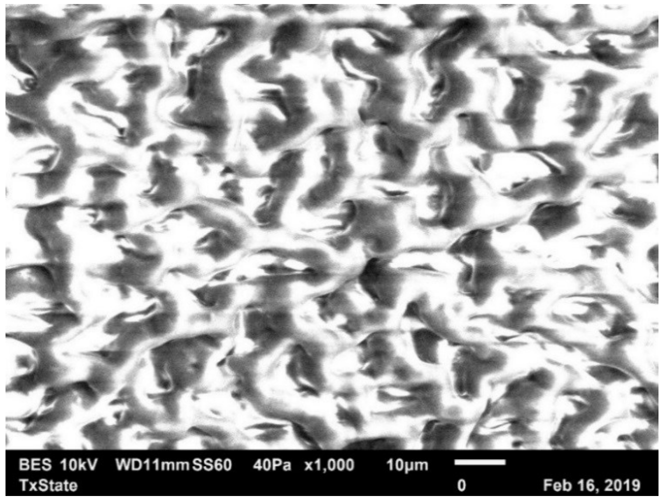


Figure 4-19. ESEM image of SIS 0% at original state

Figure 4-20 shows the image of binder containing 5% of SIS modifier. A careful observation shows that with the addition of SIS modifier into the binder, the fibrils of the network structure appear to become loose and an evolution of new phase is identified. Although the phase does not appear to be dense at this stage, a distinction can be observed through the images of with and without SIS modifier.

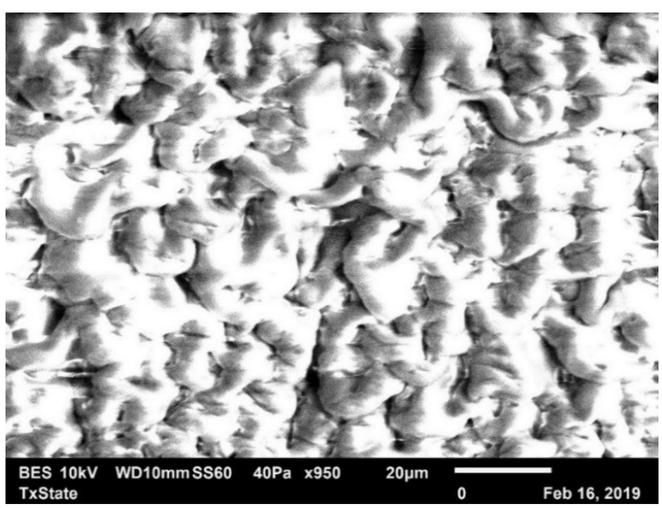


Figure 4-20. ESEM image of SIS 5% at original state

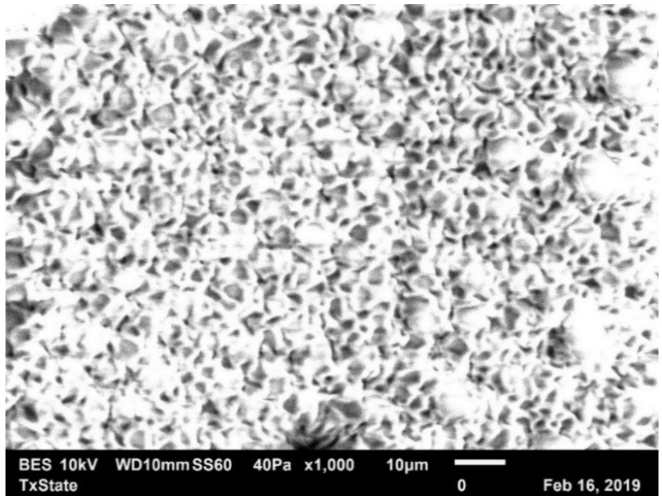


Figure 4-21. ESEM image of SIS 10% at original state

Figure 4-21 presents image of binder containing 10% of SIS modifier. The distinct round oval phase is evident from the image. The diameter of fibrils is observed to be decreased and shows an evolution of the oval phase with the percentage increase of SIS modifier. The network structure appears to be a spider net where the fibrils are the net and the oval phase is evolving from the empty space of the net.

Figure 4-22 illustrates the image captured on the binder with 15% of SIS modifier. The oval phase is observed to have an increased diameter and bulging out from the network structure. As a result, the organized fibril of the network structure becomes disoriented in size and shape.

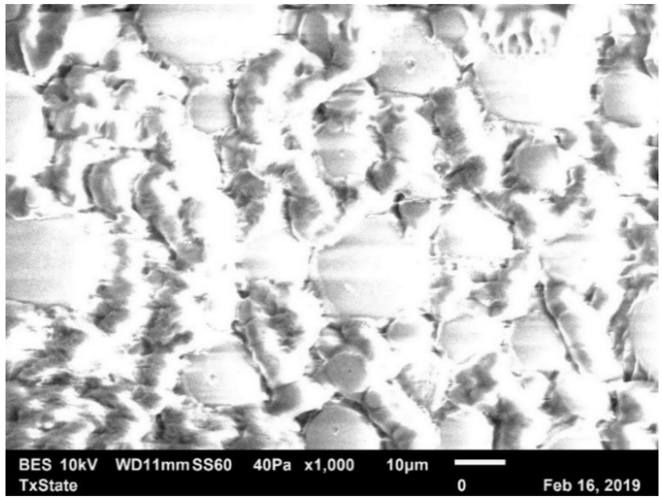


Figure 4-22. ESEM image of SIS 15% at original state

Figure 4-23 presents the ESEM image of the binder containing 20% of SIS polymer. As discussed earlier about the bulging out of the oval phase of the binder, it is clearly more evident from this image. The oval phase becomes denser and the number appears to be increased significantly. The fibril structure is almost replaced by the oval phase.

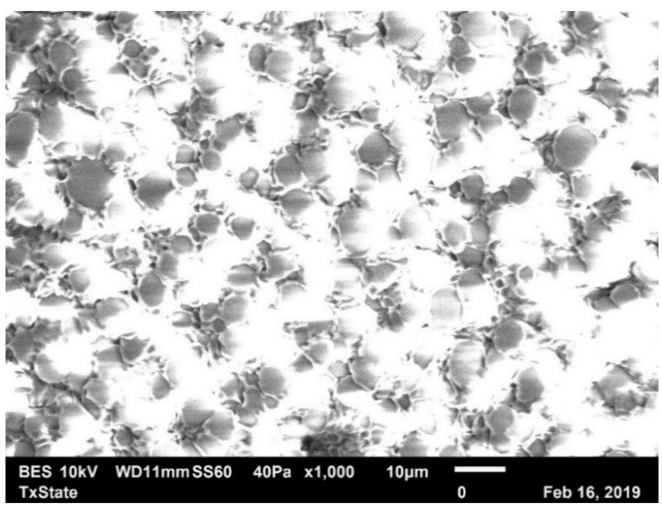


Figure 4-23. ESEM image of SIS 20% at original state

In summary, SIS modifier has significant effect on the microstructure of the control binder. The evolution of oval phase is certainly believed to have a contribution towards the stiffness of the binder. The low temperature properties obtained from BBR show that the binder becomes more cracking resistance with the percentage increase of SIS modifier which also resembles the increase of oval phase in the binder microstructure due to the amount of SIS modifier.

Ellipsometry

Ellipsometry was used to measure the optical constants of the SIS binder. Figure 4-24 illustrates the refractive index and extinction coefficient of the binders.

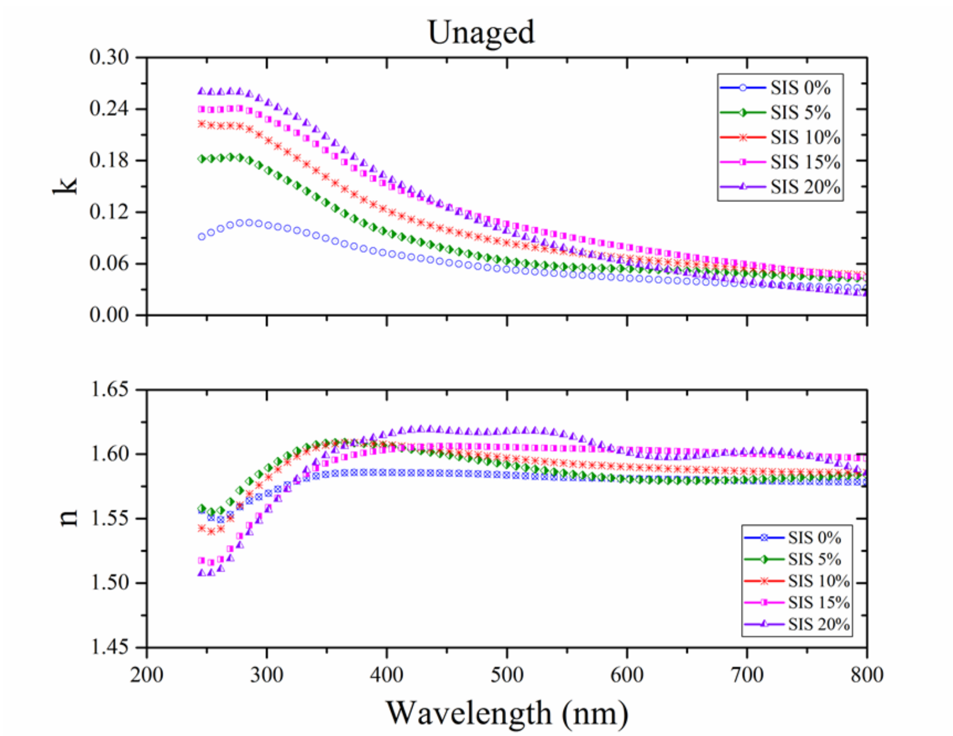


Figure 4-24. Variation in optical constants (n, k) of SIS binders

The extinction coefficient of all the binders is observed to have a decreasing function of wavelength. The binder with 20% of SIS modifier exhibited the highest absorption whereas the value is the lowest for the control binder at UV wavelength. In general the same trend is observed at visible wavelength (400-700 nm) as well. The opposite trend is found with all the binders in terms of their refractive index.

Summary and Conclusions

The objective of this chapter is to investigate the physical, rheological and microstructural properties of SIS binder. The SIS binders are produced using 0%, 5%, 10%, 15% and 20% by the weight of the control PG 64-22 binder. The viscosity property is determined by RV, rheology and stiffness properties are measured by DSR and BBR, respectively and micromorphology is investigated using AFM and ESEM. Ellipsometry is used to measure the reflection and absorption properties of the SIS binder. Based on the result of these tests, the conclusions are drawn for the materials used in this study as following,

1) SIS modifier has the potential to become a crack sealant material (blending with asphalt material) based on the physical, rheology and microscopy properties.
2) The addition of SIS content into asphalt binder can significantly increase the viscosity of binders. With the SIS percentage increased, the binder viscosity increases at both testing temperatures. However, the viscosity of SIS binder seems to have insignificant change after adding more than 15% of SIS content.
3) The amount of SIS modifier has a positive effect on the rutting resistance at high temperature.
4) The addition of SIS into asphalt binder can significantly decrease the $G^*\sin\delta$ and creep stiffness of SIS binder at low temperature which can ensure better cracking resistance of asphalt binder.
5) AFM images show the micromorphology of the binder modified with SIS modifier based on the difference of contrast between dispersed domains and

matrix. The stiffness and microstructure properties are observed to have a correlation.

6) ESEM images show the network structure and evolution of a new oval phase which has significant effect on the binder stiffness properties. With the percentage increase of SIS modifier the oval phase becomes more dominant in the network structure and is observed to play a vital role on the cracking resistance of the SIS binder.
7) In general, ellipsometry results show that the higher the SIS content, the binder exhibited higher absorption at UV wavelength.

This chapter (II) includes a part of the following publications;

Mazumder, M., Siddique, A., Lee, S.-J., "Rheological and Morphological Characterization of Styrene-Isoprene-Styrene (SIS) Modified Asphalt Binder" *to be submitted to Construction and Building Materials.*

CHAPTER V

SEALANT APPLICATION METHODS AND ITS PERFORMANCE

Introduction

In order to build a substantial body of knowledge, the main objective of this chapter is to compare the field performance of crack filling and sealing treatment as there has been little or no comprehensive research previously conducted on this topic. The tasks included the distribution of a survey questionnaires to find out why the districts in Texas do not perform crack sealing treatment, the installation of both treatment types with same sealant material and finishing techniques in four districts of Texas based upon the various climate, average daily traffic and pavement conditions, and the regular inspection of the field performance of both treatment type.

Earlier literature and survey mentioned that crack sealing can give a longer service period to the pavement life cycle before the next scheduled treatment. However, there is no accurate estimation or no study was solely conducted to compare the quantitative difference in performance between crack filling and sealing technique in Texas.

Experimental Program

Survey

A survey of crack sealing and filling procedures was developed and distributed in Texas. Questionnaires were sent to 25 districts transportation agency personnel, responses were received from 19. Texas does not currently practice routing. In general, the reasons are: i) insufficient knowledge about benefits, ii) costly and uncommon practice, and iii) lack of proper guidelines.

Installation and Monitoring

The research study is intended to compare the performance between crack filling and sealing treatment in Texas. For that purpose, four test sites have been selected presenting different climatic regions and Annual Average Daily Traffic (AADT) in Texas which are: Fort Worth, Corpus Christi Abilene (Big Spring), and Brownwood. Figure 5-1 and Table 5-1 show the detail weather information (Weather Group, LLC 2018) of the four selected test sites. Installation took place at four test locations from February to May 2016. Table 5-2 presents the installation period, treated crack length, ambient temperature and quantities of material used for each test site during construction of the two treatment types. Low traffic is determined if the AADT is less than 1000, medium traffic is determined if AADT is more than 1000 but less than 10000 and heavy traffic considered if the AADT is more than 10000.

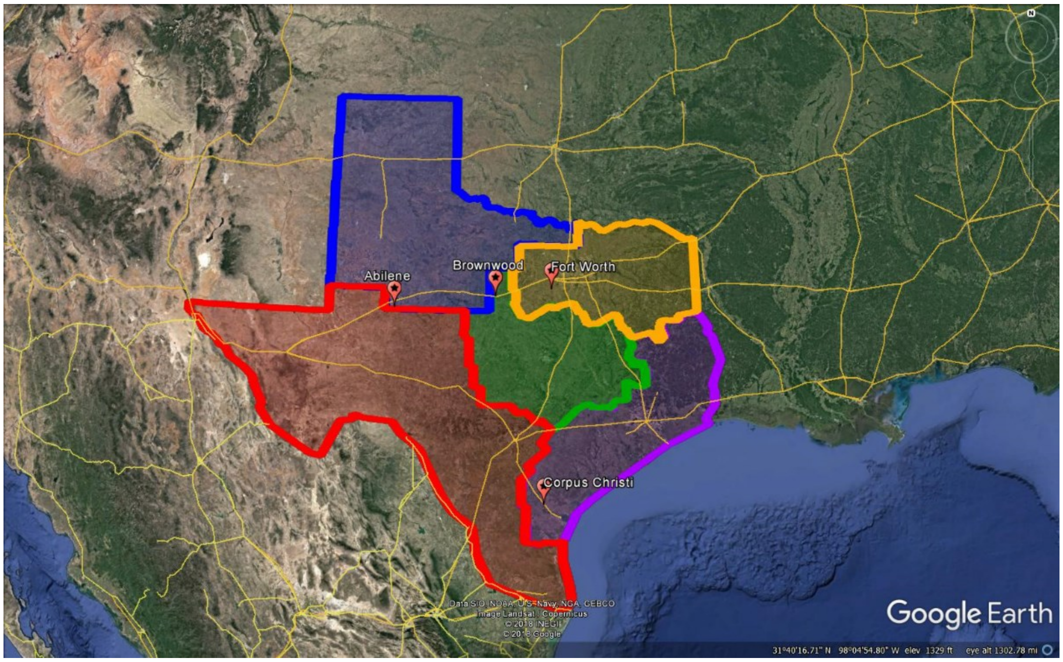


Figure 5-1. Climate zones and test sites

Table 5-1. Weather annual averages for the Districts

Year 2016				
	Fort Worth	Corpus Christi	Abilene	Brownwood
Max Temp. °F	97	95	98	97
Min Temp. °F	37	45	34	31
Range °F	60	50	64	66
Mean °F	69	75	67	66
Sum Precipitation (mm)	901.7	805.2	939.8	772.2
Year 2017				
Max Temp. °F	96	94	96	94
Min Temp. °F	40	48	33	34
Range °F	56	46	63	60
Mean °F	70	75	66	66
Sum Precipitation (mm)	929.6	764.5	530.9	759.5

Table 5-2. Treated crack length, quantities of sealant material and ambient air temperature of the test sections during installation

District	Installation Date	Treatment type	Crack length (m)	Material (kg)	Temperature (°F)
Fort Worth	02/25/2016	Filling	125	109	55.4
		Sealing	90		
Corpus Christi	05/04/2016	Filling	98	122	89.6
		Sealing	52		
Abilene	02/26/2016	Filling	190	123	33.8
		Sealing	100		
Brownwood	04/01/2016	Filling	95	82	53.6
		Sealing	66		

Districts and pavements were chosen based on situation in a particular climate zone. Besides the environmental factors, the study selected sealing and filling cracks in pavement that is 3-5 years old. At this age, the pavement is still generally in good enough shape that proper crack treatment should seal out water and extend the service life of the asphalt. Also, it is not too old that routing it may cause damage. By treating cracks in younger pavements, it is possible to mitigate the formation of additional secondary cracks, and prevent the intrusion of water into the base. The selected test sites were 3-5 years old and had a combination of transverse and longitudinal cracks. The selected test sites had no secondary cracking. The selected pavement had minimal or no alligator (fatigue) cracking, as that indicates a structural failure, and crack sealing or filling is not an effective treatment once structural failure has occurred. The severity of the transverse and longitudinal cracks was low to moderate. High severity cracking in pavement that young indicates other issues may be at play. Additionally, minimal or no representation of other types of cracks, such as block or reflective cracking was considered as another condition for choosing the test site. Lastly, The Districts should not have any plans to overlay the section until crack sealant material failure occurs.

Winter and spring months were selected to perform the installation. The same contractor was awarded the contract for performing routing and sealing at each site in order to maintain smooth transition in between routing and sealing work. Installation was done by the same crew member in all test sites. TxDOT was given the contract for traffic control. Two types of cracks were selected for the installation which were 3 mm or approximately 1/8" in width. The first one is longitudinal cracks which develop longitudinally along the pavement centerline. Another one is transverse cracks which occur perpendicularly to the center line of the pavement. Crack filling and sealing treatments were given to two types of cracks at each site on the wheelpath with proper designation so that all the cracks can be easily distinguished. All the selected cracks at each site were mapped with GPS coordinate using GPS camera so that monitoring can be done smoothly after installation. Crack sealing treatment designated cracks were routed before putting the sealant material into the cracks. Routing incorporates the use of a router to open all the cracks up to a uniform width and depth. A router with carbide teeth was used to provide routing on a 1x1 profile (cutting as wide as deep) or 12 mm by 12 mm.

Crack cleaning is the most important phase of a successful installation as it reduces the adhesion failures between the sealer material and the sidewall of the crack. For the proper cleaning of each crack at each location high pressure air blasting was used. After ensuring that pavement surface was free from moisture, hot pour sealant material was squeegeed flush to the surface of the road so that it can provide a smooth drive to the drivers. The road was reopened to traffic after the sealant material get cured. In general, 25 minutes of curing time was given to cure the sealant materials. Figure 5-2 shows the different phase of the research study.

In order to monitor the performance of these two types of treatment, the test sites were visited once after a three month period of interval for approximately one and half years. In general, four successive monitoring were conducted after the first one. Evaluation of the performance of these two application methods were based on visual assessment and regular inspections. Based upon the inspections and measured failure length of treated cracks by measuring wheel, collected information was used to measure the rate of failure and effectiveness of each treatment. The AASHTO PP20-95 procedure was used to calculate the percentage of effectiveness of each treatment. The research team determined the treatment effectiveness by establishing how much of treatment has failed in relation to the total length of treatment applied. Percent failure = (failed length after treatment/total length of treatment) x 100. After that the treatment's effectiveness can be calculated by subtracting the percentage of treatment failure from 100 percent (Effectiveness = 100 - Percent failure). After a number of inspections a graph of effectiveness versus time can be developed. Modes of stress or loss that might indicate the treatment failure were noted in the following forms: The main mode of stress or loss considered were opening or loss of sealant of previously sealed cracks, adhesion or cohesion loss, pull out and spalls. After a number of inspections a graph of effectiveness versus time was developed to show the percentage effectiveness of each treatment at each test site.

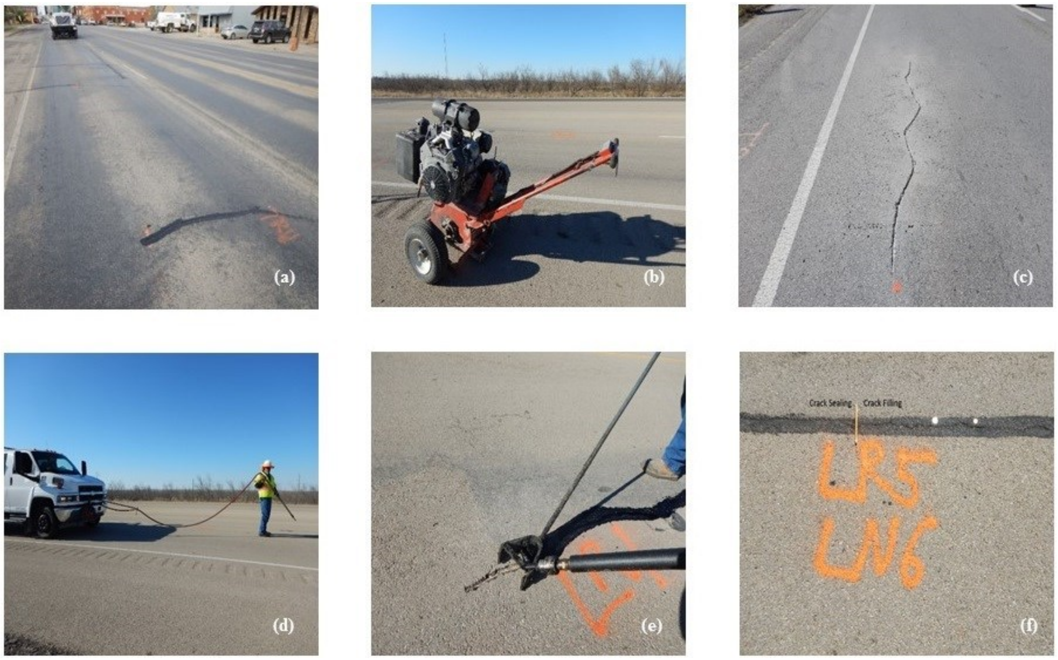


Figure 5-2. Crack treatment process (a) Longitudinal and transverse cracks; (b) Router; (c); Routing of cracks; (d) Cleaning of cracks; (e) Placing of sealant material with squeegeed flush to the surface of the road; (f) Evaluation of the performance

Performance Evaluation of the Test Sections

Fort Worth

In Fort Worth district, crack sealing and filling treatments were installed at the highway of US 377 on 25 February 2016. It was a sunny day and 55 °F when the contractor started working. This section is a four lane highway with heavy truck traffic. Longitudinal and transverse cracks were selected and sealed with both treatment types. The first monitoring was performed on 13 May 2016 (74 °F). The next four site visits were made on 16 August 2016 (78 °F), 19 November 2016 (59 °F), 2 February 2017 (43 °F) and 14 April 2017 (69 °F). Figure 5-3 presents the performance trends of longitudinal and transverse cracks treated with crack sealing and filling treatment.

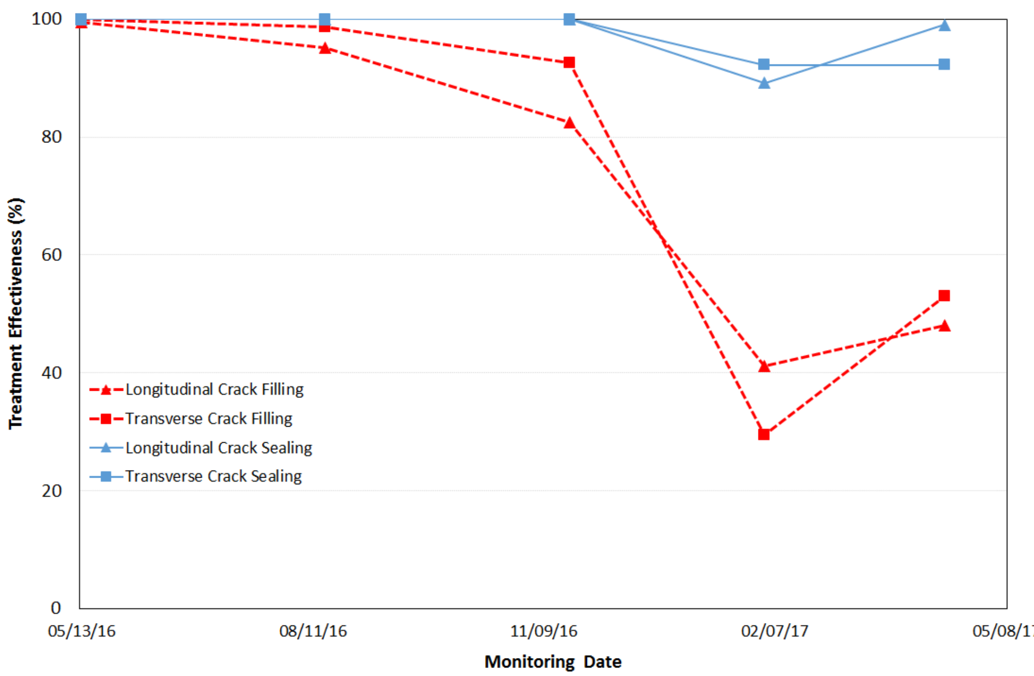


Figure 5-3. Performance trends of treated cracks in Fort Worth district

Cracks treated with sealing treatment showed excellent performance compared with crack filling treatment in this section. Both longitudinal and transverse cracks treated with sealing treatment were observed to have 100% treatment effectiveness after three investigations period which was nine months after the installation. On the other hand, the longitudinal and transverse cracks with filling treatment were found to have the treatment effectiveness rating of 82.5% and 92.6%, respectively. The treatment effectiveness of longitudinal and transverse cracks with filling treatment dropped to 41.1% and 29.5%, respectively during the winter of 2017. This can be attributed to the fact that during winter month cracks open at its best. However, in contrast, longitudinal and transverse cracks which had sealing treatment scored a treatment effectiveness of 89.2% and 92.2%, respectively. By the fifth or final investigation, longitudinal cracks with filling and sealing treatment were found to have a treatment effectiveness of 48% and 99%, respectively. The increase in treatment effectiveness was the result of healing effect due to the high temperature. Transverse filling and sealing seemed to have same trend with 53.1% and 92.2% treatment effectiveness, respectively.

Figure 5-4 presents the overall treatment effectiveness of crack filling and sealing treatment for each monitoring period. Cracks with sealing treatment outperformed the crack filling treatment. Overall, 48.5% and 98.8% treatment effectiveness was observed for crack filling and sealing treatment, respectively, during the final investigation.

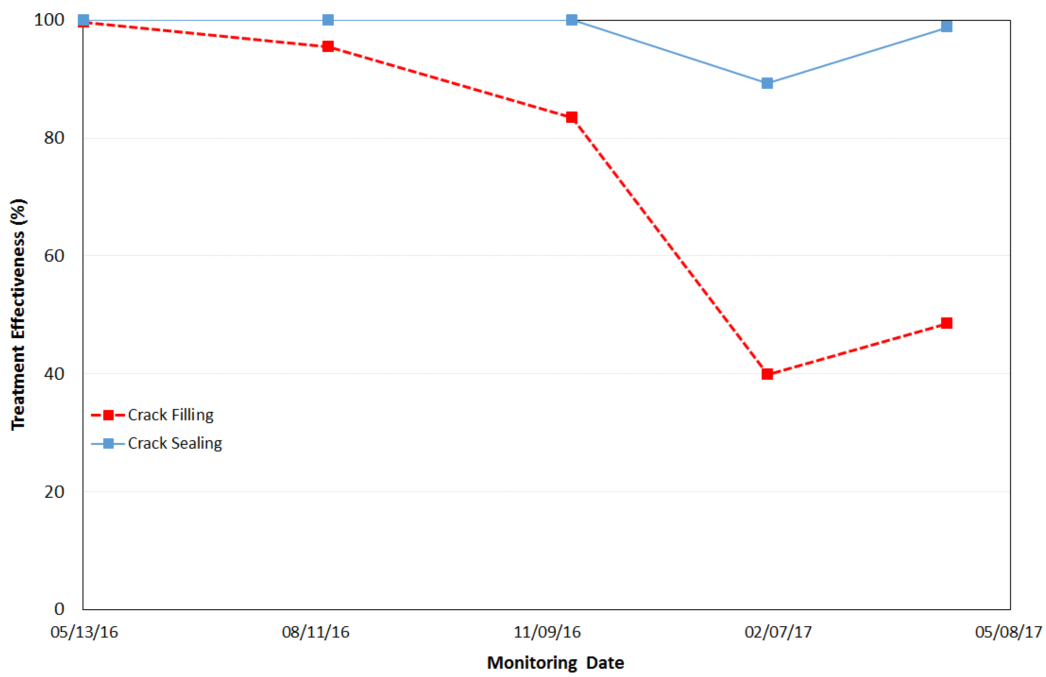


Figure 5-4. Performance of crack filling and sealing treatment in Fort Worth district

Corpus Christi

All selected longitudinal and transverse cracks at the Highway of 2292 Rand Morgan Rd. were installed on 4 May 2016 using two different types of crack treatment. This four lane test site has low traffic. The ambient temperature was recorded 89 °F during construction. The four investigations to evaluate the performance of the crack treatment were conducted on 15 August 2016 (80 °F), 12 November 2016 (64 °F), 2 February 2017 (48 °F) and 8 April 2016 (75 °F). Figure 5-5 shows the performance trends of treated cracks with crack filling and sealing treatment.

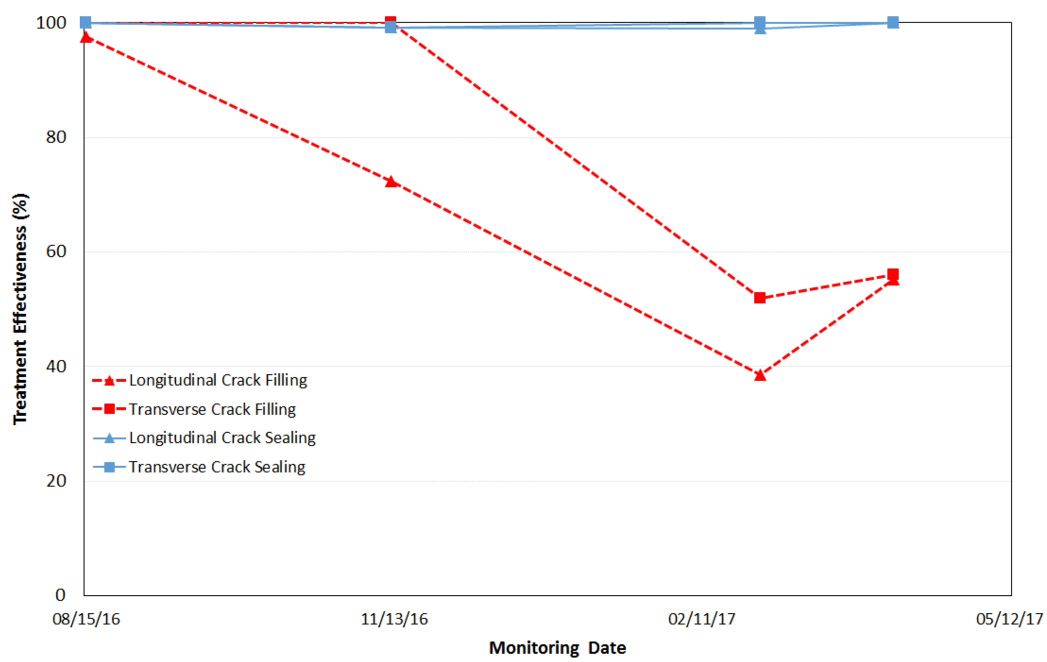


Figure 5-5. Performance trends of treated cracks in Corpus Christi district

It is evident from the figure that cracks treated with sealing treatment exhibited excellent performance with a treatment effectiveness of approximately 100% at each monitoring period regardless of the crack types. Longitudinal and transverse filling had experienced 44.8% and 44.0% failure, respectively, by the final investigation period.

Figure 5-6 depicts the average treatment effectiveness of all the cracks treated with crack filling and sealing. After four investigation period it was found that sealing treatment effectiveness (100%) in this test site was approximately twice compared to the filling treatment (55.2%).

Figure 5-6. Performance of crack filling and sealing treatment in Corpus Christi district

Abilene

In the Abilene test site, only longitudinal cracks were selected at the highway of US 87 for the crack treatment. Two treatments were installed on 26 February 2016 with an ambient temperature of 34 °F. This site is a four-lane divided highway at Howard county, southbound lanes of US 87 from RM 33 to the Glasscock county line with heavy truck traffic. The first test site evaluation was done on 13 May 2016 (77 °F). Rest of the four investigations were carried out on 16 August 2016 (80 °F), 19 November 2016 (48 °F), 2 February 2017 (39 °F) and 14 April 2017 (77 °F). Figure 5-7 presents the performance trends of treated longitudinal cracks with crack filling and sealing treatment.

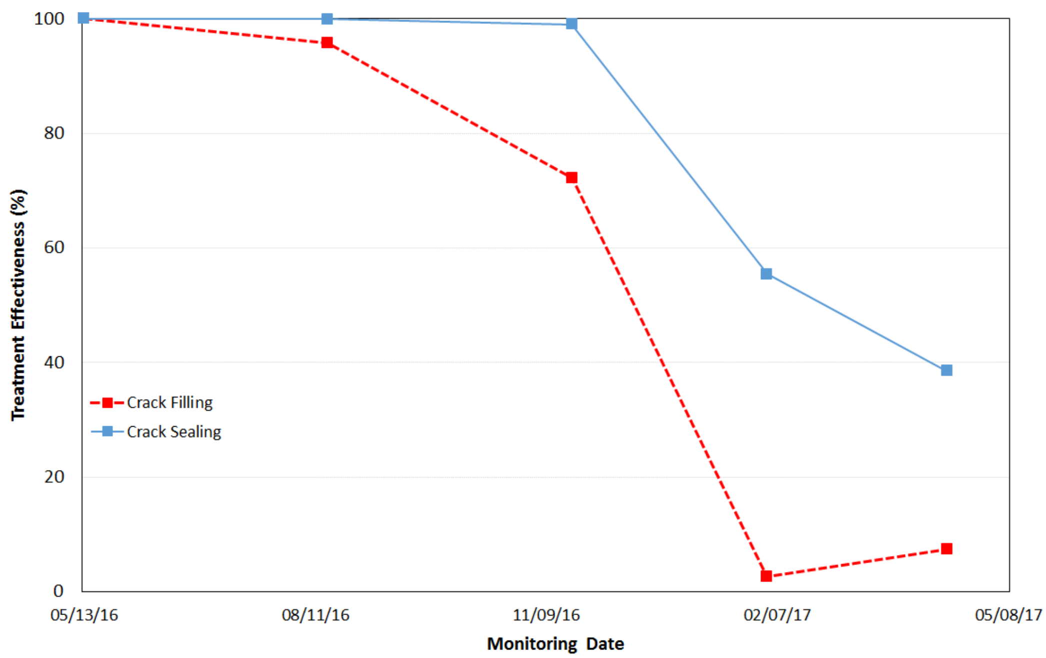


Figure 5-7. Performance of crack filling and sealing treatment in Abilene district

Despite the low treatment effectiveness of sealing treatment in this test site, it was much higher than crack filling treatment. After three investigation period, sealing and filling had a treatment effectiveness of 99.0% and 72.2%, respectively. A rapid increase in failure rate was observed during the winter of 2017 for both treatment types. By the final investigation during the spring of 2017, crack filling (7.5%) and crack sealing (38.5%) exhibited failure in more than half of the treated cracks.

<u>Brownwood</u>

Longitudinal and transverse cracks were selected at the highway of SH 6 East 8th street and sealed using crack sealing and filling techniques on April 1 2016 when the ambient temperature was 53 °F. This test site is a four lane divided highway with medium traffic. The five site monitorings were conducted on 13 May 2016 (86 °F), 16 August 2016 (80 °F), 19 November 2016 (48 °F), 2 February 2017 (39 °F) and 14 April 2017 (77 °F).

Figure 5-8 depicts the performance trends of treated longitudinal and transverse cracks with crack sealing and filling technique.

Figure 5-8. Performance trends of treated cracks in Brownwood district

Similar to the other test sites, crack sealing treatment achieved a high treatment effectiveness compared to filling technique. Longitudinal cracks treated with sealing scored a treatment effectiveness of 89.3% whereas filling technique had 60.4% after final investigation. In contrast, less difference in treatment effectiveness (48.1% and 56.6% with filling and sealing treatment, respectively) was found for transverse cracks. The reason is that in this test site most of the treated transverse cracks with sealing treatment were propagated from the shoulder lane to the traffic lane. During installation, the cracks at the vehicle lane were routed and sealed. As a result, during winter the shoulder crack propagated to the sealed cracks and caused adhesion failure to the sealant materials due to the penetration of water through the non-treated shoulder cracks. Otherwise high treatment effectiveness could be expected based on the condition observed with other properly treated cracks with sealing technique.

Figure 5-9 shows the overall treatment effectiveness of the treated cracks with this two treatment techniques. On an average the crack sealing and filling treatment effectiveness for this site found to have 79.6% and 56.2%, respectively, after the final investigation.

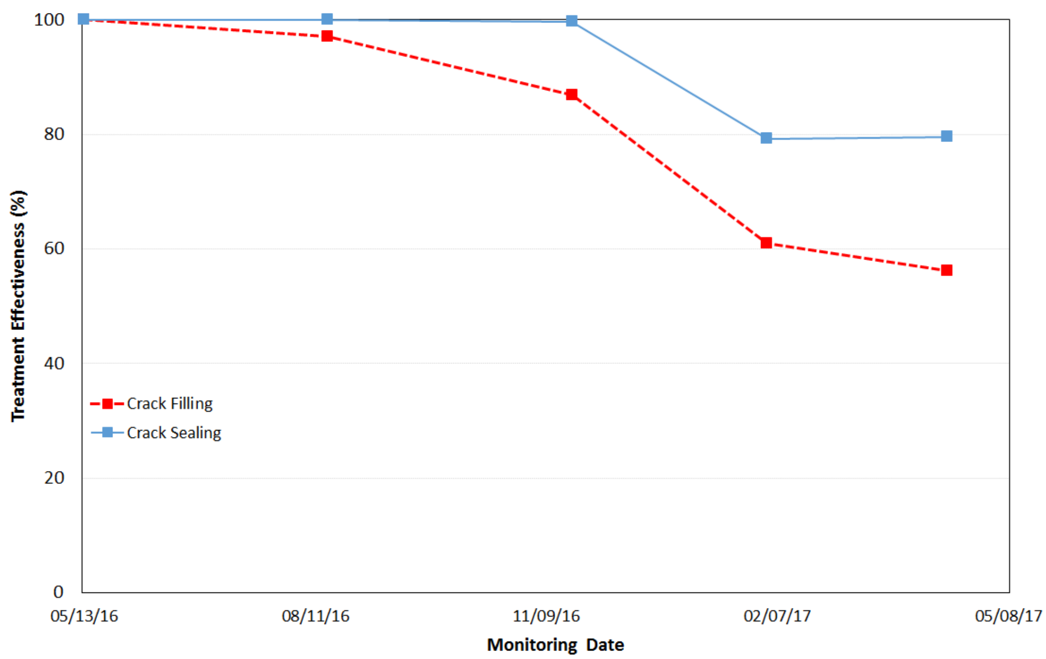


Figure 5-9. Performance of crack filling and sealing treatment in Brownwood district

Discussions of the Results

In Texas, four districts with various traffic and weather conditions were selected for the installation of two different types of crack treatment methods. The test sections were visited once after a three month period of interval. The discussions of the results organize the performance trend of crack sealing and filling treatment in different districts at each monitoring period.

During the first investigation both crack sealing and filling were observed to have excellent performance regardless of the test site, with filling having an average treatment effectiveness of 99.3% and sealing exhibiting no failure rate. The second investigation was performed after six months of installation and both treatment seemed to have good short term performance. On an average, the treatment effectiveness of crack sealing (99.8%) was slightly better than filling (90.2%) treatment. However, Corpus Christi site had encountered 27.7% damage with filling technique. The reason is that the second investigation in this site was conducted during fall when cracks started to open and for other test sites it was during summer. The high performance of crack sealing treatment (99.5%) remained same in all test sites until the end of third investigation which was after nine months of construction whereas filling technique was observed to have decreased treatment effectiveness. The average treatment effectiveness dropped by approximately 30% with filling technique. Table 5-3 shows the individual and average treatment effectiveness of different test sites at each monitoring period.

Table 5-3. Average treatment effectiveness of crack treatment methods corresponding to each monitoring period

Monitoring No.	Treatment Types	Treatment effectiveness (%)				Average (%)
		Climate conditions, traffic and corresponding districts				
		Wet-Warm	Wet-Cold	Mixed	Dry-Cold	
		Low	High	Medium	High	
		Corpus Christi	Fort Worth	Brownwood	Abilene	
1st	Filling	97.5	99.6	100	100	99.3
	Sealing	100	100	100	100	100
2nd	Filling	72.3	95.5	97.1	95.7	90.2
	Sealing	99.2	100	100	99.9	99.8
3rd	Filling	39.1	83.5	86.9	72.2	70.4
	Sealing	99.4	100	99.7	99	99.5
4th	Filling	55.2	39.9	61	2.7	39.7
	Sealing	100	89.3	79.2	55.4	80.7
5th	Filling	-	48.5	56.2	7.5	37.4
	Sealing	-	98.8	79.6	38.5	72.3

During the monitoring in the winter of 2017, both crack techniques showed a general decreasing trend in treatment effectiveness due to the opening of the crack. On an average, the effectiveness of crack filling and sealing declined to 43% and 19%, respectively. The effect is more severe in Abilene test site where filling and sealing treatment effectiveness dropped by 69.5% and 43.6%, respectively. The reason is that the treated cracks in this test site were selected at the construction joint of the two pavement and these joint cracks opened more than the vehicle lane crack. The cracks with filling technique in Corpus Christi had encountered 33.2% damage whereas no failure rate was observed with sealing. In Brownwood test site, the percentage deterioration rate was found quite close for both treatment types (25.9% and 20.5% for filling and sealing, respectively). Improper sealing treatment of transverse cracks is the reason behind the less difference in results. The reduction rate in Fort Worth due to the winter was more intense with filling (43.6%) compared to sealing (10.7%) technique. The main failure criteria for crack filling treated cracks were observed as loss of sealant materials and formation of secondary cracks. On the other hand, adhesion failure was observed as the failure characteristics for crack sealing treated cracks. Figure 5-10 presents the visual assessment and failure characteristics at different test sites.

Figure 5-10. Visual assessment of crack treatment: (a) and (b) Loss of sealant material with filling treatment; (c) and (d) Adhesion failure of sealant material with sealing treatment; (e) Total failure observed with filling treatment for longitudinal crack; (f) Comparison between the two types of treatment

Overall, average treatment effectiveness of 35.7% and 80.5% was achieved with filling and sealing treatment, respectively, after the winter investigation. Figure 5-11 and 5-12 present the performance trend of crack filling and sealing technique in different test sections. It is evident from the results that sealing technique is very effective to prevent the deterioration of the pavement during winter months.

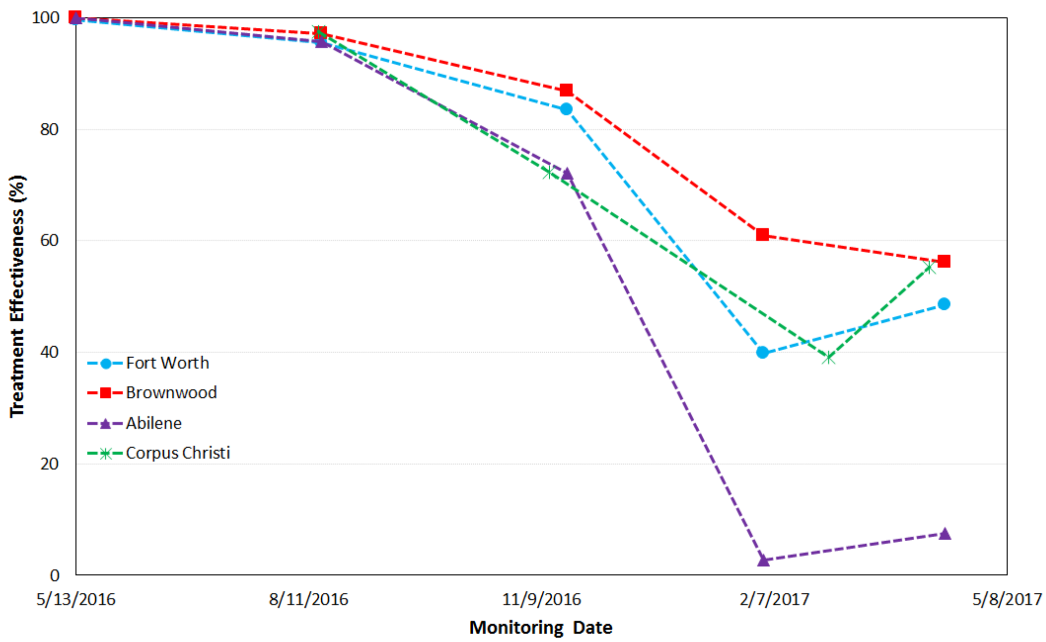


Figure 5-11. Performance trends of crack filling treatment in different test site

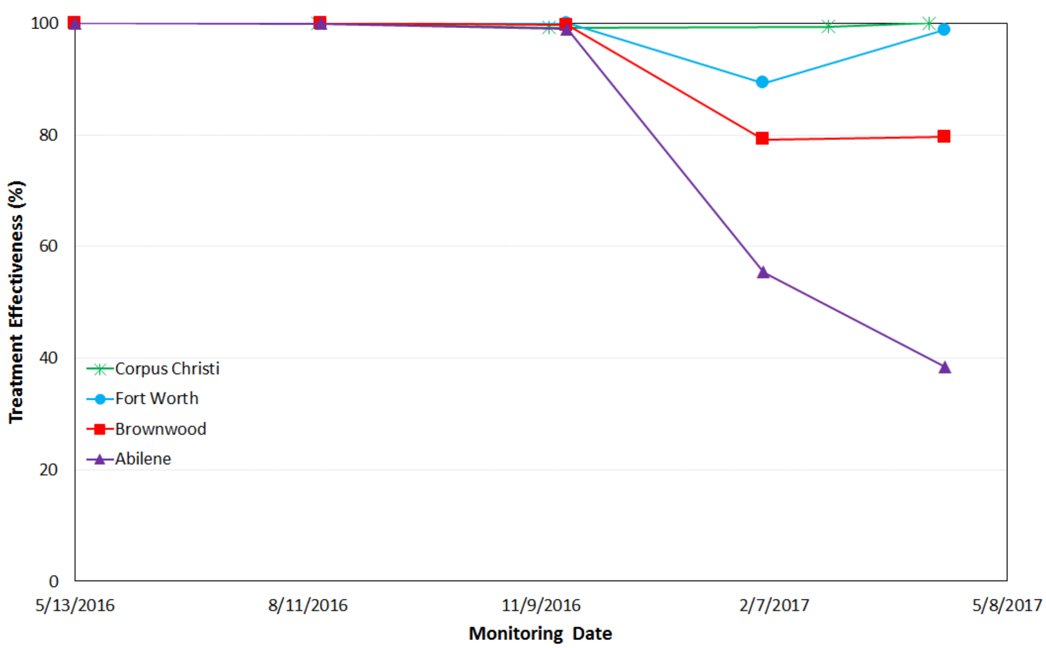


Figure 5-12. Performance trends of crack sealing treatment in different test site

In the final investigation, it was found that the average treatment effectiveness of crack sealing treatment is approximately double compared to filling technique based on the three test site. Corpus Christi and Fort Worth site were observed to have little improvement in treatment effectiveness due to the contraction of the pavement after winter. On an average 12.4% and 5.1% raise in effectiveness was found for filling and sealing, respectively. The restoration of treatment effectiveness in summer season was observed to have a correlation with the maximum annual temperature and annual temperature range. As this phenomena depends on the natural process of cracks openings in the winter and closing in the summer along with the pavement, soil and annual precipitation. It was found that high recovery was obtained with the district with lower annual temperature range (Fort Worth and Corpus Christi). There was no significant recovery was observed in crack treatment methods at Abilene and Brownwood test site due to high temperature.

Also, traffic condition differs from district to district and sealant performance also depends on this factor as well. Based on the AADT data, Abilene and Fort Worth consist of heavy traffic, Brownwood consists of medium traffic and Corpus Christi has low traffic. In general, it is evident from the data that Fort Worth and Abilene have less treatment effectiveness with both treatment types (Brownwood has less treatment effectiveness with crack sealing due to the implementation of improper guidelines) compared to the other test sites. It is due to the heavy traffic in both test sites. Between Fort Worth and Abilene, Abilene has more heavy duty trucks compared to Fort Worth test site which is one of the reason of less treatment effectiveness in Abilene test site. Between Brownwood and Corpus Christi, Corpus Christi has the highest treatment effectiveness after the final investigation which consists of low traffic volume. Based on the aforementioned discussion it is found that both treatment type has experienced adverse effect due to the heavy-duty trucks.

Also, based on the experience from this study it has been observed that crack sealing treatment perform better if the crack has a width of minimum 5 mm (0.2 inch) to maximum 19 mm (0.75 inch). For Texas, routing profile of 1x1 has the potential to enhance performance with sealing treatment. On the other hand, crack filling treatment can perform good if the crack has a width of minimum 5 mm (0.2 inch) to maximum 25 mm (1 inch). Crack sealing outperformed filling treatment in every test sections. Approximately 50% more treatment effectiveness was achieved with sealing than filling technique in Fort Worth and Corpus Christi test section. Brownwood site had attained more than 20% treatment effectiveness with sealing treatment even though the improper crack sealing treatment of transverse cracks. It is expected that given the proper crack sealing treatment in Brownwood site would have the same performance like earlier test site. Both treatment type did not perform well due to the nature of the crack selection in Abilene test section. However, sealing performed better than filling treatment.

Summary and Conclusions

The study was conducted to compare the field performance between crack filling and sealing techniques in Texas. Four test sections in four different districts were selected and monitored regularly once after three months to evaluate the performance of two treatment types. Based on the results of the study, following conclusions can be drawn:

1) According to the response of nineteen Texas districts, crack sealing is not a favorable option due to the high initial cost and lack of guidelines or knowledge about performance, the time consumption, and equipment issue.

2) In between sealing and filling technique, sealing scored a high treatment effectiveness in all test site after the final investigation. Treatment effectiveness of 50.3%, 44.8%, 31% and 23.4% more was obtained in Fort Worth, Corpus Christi, Brownwood and Abilene, respectively, with sealing compared to filling treatment.

3) On an average, treatment effectiveness of sealing technique was declined by 19% whereas 43% reduction was observed for filling technique due to winter weather.

4) Appropriate crack selection and following proper guidelines during the installation of crack sealing treatment can give a long term cost effectiveness to the transportation agency.

This chapter (V) includes a part of the following publications;

Mazumder, M., Kim, H. H., Lee, S.-J., "Comparison of Field Performance of Crack Treatment Methods in Asphalt Pavement of Texas" *Journal of Transportation Engineering, Part B: Pavements, ASCE,* Vol. 145(1), pp. 04018057-9 (November 2018).

Mazumder, M., Kim, H. H., Lee, S.-J., "Comparison of Field Performance of Crack Treatment Methods in Asphalt Pavement: Crack Filling versus Crack Sealing" *In: 97th TRB Annual Meeting, Transportation Research Board*. Washington, D.C., Jan. 2018.

Mazumder, M., Kim, H. H., Lee, S.-J., Lee, M. S., "Crack Treatment Performance on Pavement Marking, Joint and Shoulder Lanes in Texas" *Innovative Infrastructure Solutions*, 4:16, https://doi.org/10.1007/s41062-019-0202-7 (February 2019).

CHAPTER VI

COST EFFECTIVENESS OF SEALANT APPLICATION METHODS

Introduction

In this chapter the highway design and maintenance standard model (HDM-III) is used in order to evaluate the environmental conditions (altitude and rainfall), road length and the effects of ADT on the cost of maintaining a given section with two different methods of crack sealing. These are i) routing (sealing) and ii) non- routing (filling) methods. HDM-III is a computer program for analyzing the total transport costs of alternative road improvement and maintenance strategies through life-cycle economic evaluation. In order to achieve accurate simulations, each potential variable with an impact was identified and its effect on the overall process assessed, allowing an economic analysis of the HDM-III program inputs to be performed. After the critical inputs were identified, the simulations were run in HDM-III in order to find the best cost effectiveness practice between the routing and non-routing methods.

Also, previous studies analyzed the cost effectiveness of crack treatments based upon the field performance or prediction model rather than cost data analysis from the field. Results from the SHRP study showed that there is almost a 40 percent greater chance of sealant success if cracks are routed prior to sealing. Since there is very limited comprehensive study to find out the initial and long term cost effectiveness in between crack sealing and filling using real field cost data, this study attempted to achieve this objective. The comparison of the construction cost between crack sealing and filling treatment in terms of initial cost and life cycle cost using field cost input also documented in this chapter.

HDM-III Modelling

Between 1973 and 1982, the World Bank initiated four studies in four different countries (Kenya, Caribbean, India and Brazil) to develop road deterioration models to evaluate what effect construction and maintenance activities had on roads.

These studies were:

- Kenya study (Abaynayaka et al. 1977): Develop relationships for road deterioration and road user cost.
- Caribbean study (Morosiuk andAbaynayaka 1982): Compared road geometry effect on vehicle operating costs.
- India study (CRRI 1982): Investigated operational concerns on Indian roads
- Brazil study (GEIPOT 1982): Validated previous model relationships

Based on all the research, the World Bank developed a comprehensive deterioration model in 1987 for use with the personal computer in 1995. This model is known as HDM-III. Figure 6-1 represents the highway and maintenance standard model.

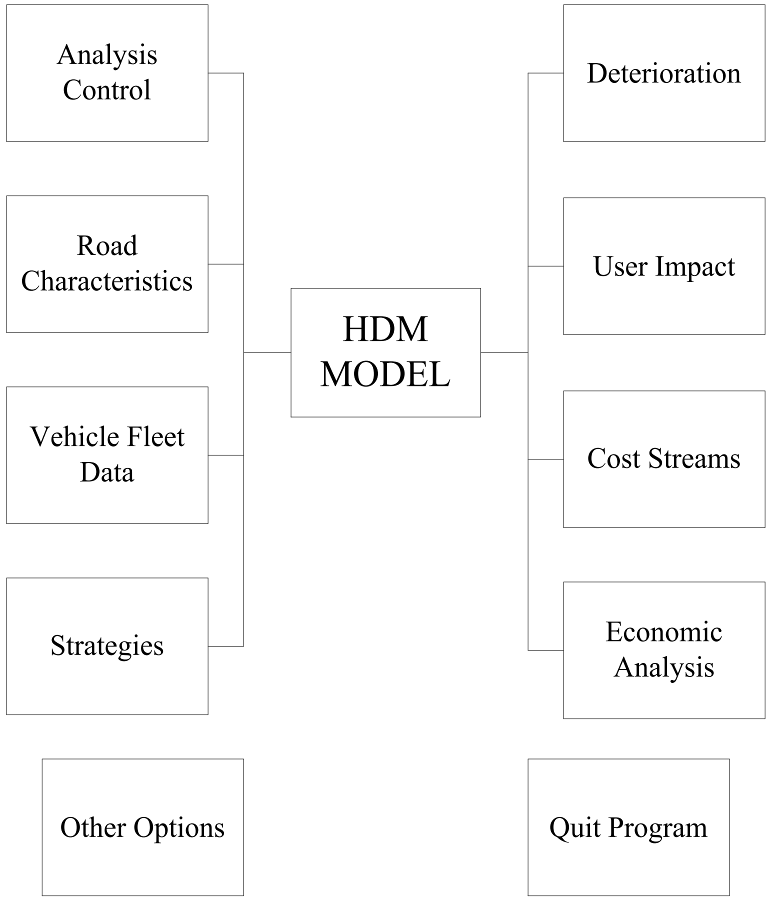


Figure 6-1. HDM-III model

HDM-III was designed to evaluate a set of road agency strategies for paved and unpaved roads. The program computes, for each of the road agency strategies being evaluated, the road deterioration, the cost streams (agency cost and capital cost), and the economic indicators (net present value of net benefits) used to compare the set of road agency strategies. As a result, the user obtains the appropriate strategy that yields the highest benefits to an agency. Also, if there is a budgetary constraint, the user obtains the optimal strategy as a function of the budget constraint.

Methodology and Modelling

There were a potential 106 inputs concerning paved roads. Since there were only two methods (routing and non-routing) for paved roads, most of the inputs were the same. The input variable for possible significant differences between these two methods was identified in terms of cost effectiveness. Maintenance intervals and material cost were found to have the greatest impact. Variables such as the environmental conditions (including altitude and rainfall), material condition, and other non-cost related variables had no relevant impact on the overall cost evaluation.

Three variable inputs were considered as follows:

i) Average daily traffic (ADT)

ii) Altitude

iii) Road length

Another important feature of HDM-III was that while running simulation the user needed to provide maintenance strategies. Each strategy is composed of one or more road agency policies valid for a certain period. Generally, the program analyzes five strategies, only two strategies were used for this study. Of the two strategies being defined, the first strategy was crack filling without a routing method and the second strategy was crack sealing with a routing method. The cost effectiveness between these two strategies was based on two categories:

i) Initial cost

ii) Durability of pavement after the treatment of two configurations.

According to TxDOT, sealing with routing costs range from $1.20 to $2.50 per foot whereas sealing without routing costs range from $0.15 to $1.10 per foot crack. Also, from the literature review, the Indiana Department of Transportation (INDOT) was considered as a good example of practicing crack sealing. According to INDOT, cost for filling was $750/lane mile and rout/seal was $1,100/lane mile. Based on this data, the initial cost of crack sealing with routing method is more costly compared with the non-routing method. After an intensive literature review and survey, the routing method was determined to cost 50% more compared against the non-routing method. The main assumption was that the price value might change depending upon variables but the trend of 50% increasing would be the same. According to the literature review and survey from the Texas Districts, the research team considered the pavement could perform satisfactorily without routing for 3 years and with routing for 5 years. The two strategies are shown in Table 6-1.

Table 6-1. Strategy for HDM-III

For 25 years (Starting from 2015)	
1st Strategy, S1 (without routing)	2nd Strategy, S2 (with routing)
Reseal after 3 years	Reseal after 5 years

Along with the two strategies, three input variable simulations were run in HDM-III. As both methods were used for paved roads, most inputs were selected as a default. The economic analysis between the routing and non-routing methods was performed in terms of agency cost, capital cost and net present value.

Agency cost is defined as the expenses incurred by the agency. The total road capital cost in any year comprises all the costs incurred in that year for the construction option applied to the link-alternative and all road maintenance operations that are classified as capital. Net present value is defined as a calculation that compares the amount invested today to the present value of the future cash receipts from the investment. In other words, the amount invested is compared to the future cash amounts after they are discounted by a specified rate of return.

The study also includes the selection of cost effective strategy with the percentage increase in cost due to routing. For this case, six strategies were defined for different interval years ranging from 3 years to 8 years and resulting in a percentage increase in financial cost. Performing maintenance with routing exceeds the cost of the non-routing method in terms of agency and capital cost for each particular year. Each particular year period not sealed before performing the next maintenance is considered as a cost effective strategy for that percentage increase.

Results and Discussions

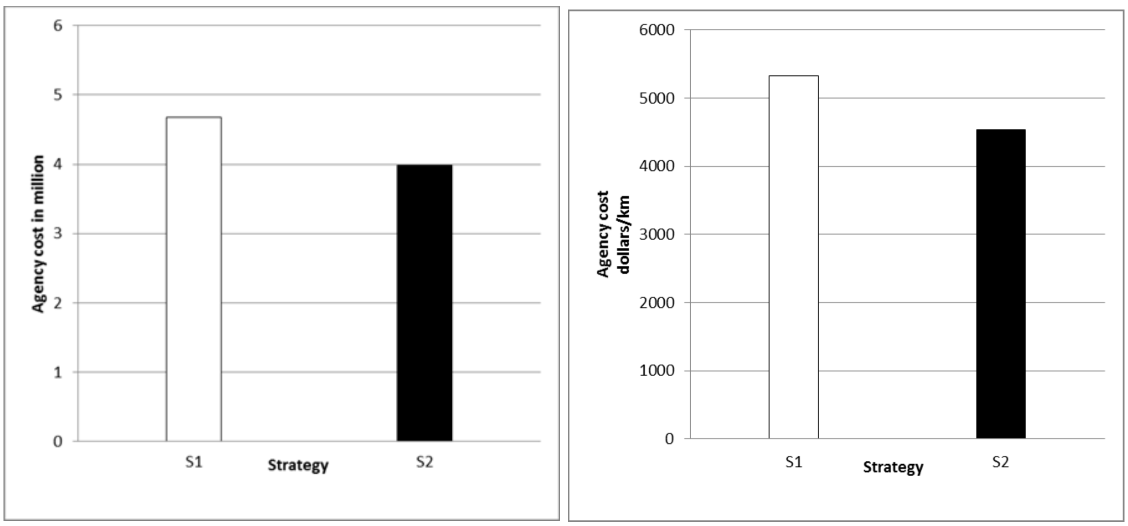
The key objective of this study was to determine the most cost effective maintenance practice between routing and non-routing methods of crack sealing. To determine the maintenance giving the minimum life cycle cost based upon ADT, altitude and road length was achieved by HDM-III in terms of agency cost, capital cost and net present value. Also, simulations were performed to select the cost effective strategy with the increasing of unit cost due to routing method.

ADT analysis

ADT was varied from 100 to 3000 with an interval of 200 based on the location. In total there were 15 simulations run in order to figure out the agency, capital and net present value between routing and non-routing configurations based on a 25-year analysis period. It is evident from Figure 6-2 that agency cost for routing configuration is less than non-routing configuration.

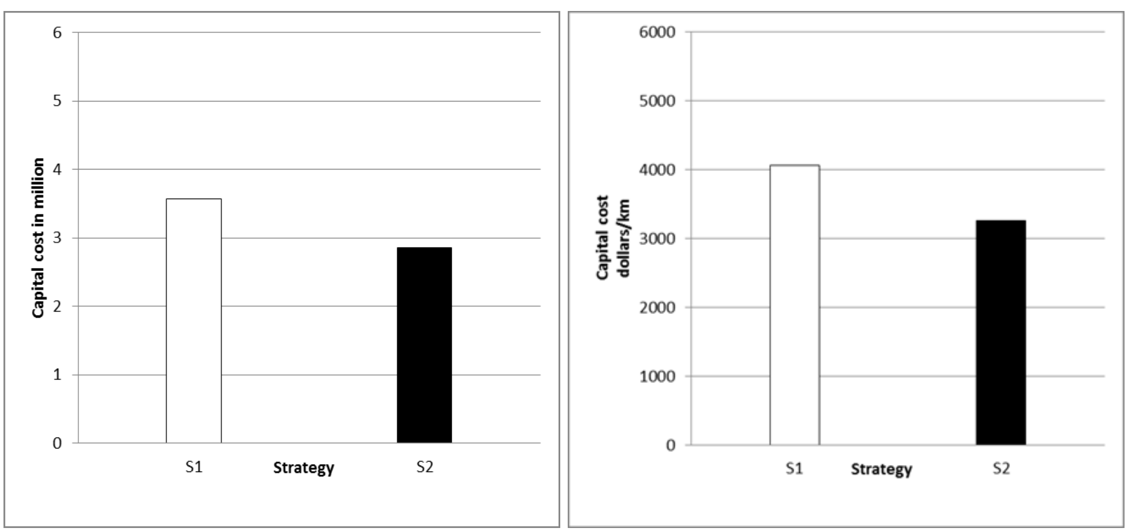
It has shown that agency cost could be approximately 15% less with routing configuration compared with non-routing configuration based on a 25-year period.

Also the same trend happened with the capital cost. The non-routing configuration can cause 24% more expense compared to routing configuration. Figure 6-3 illustrated the capital cost.



S_1: Without routing, S_2: With routing

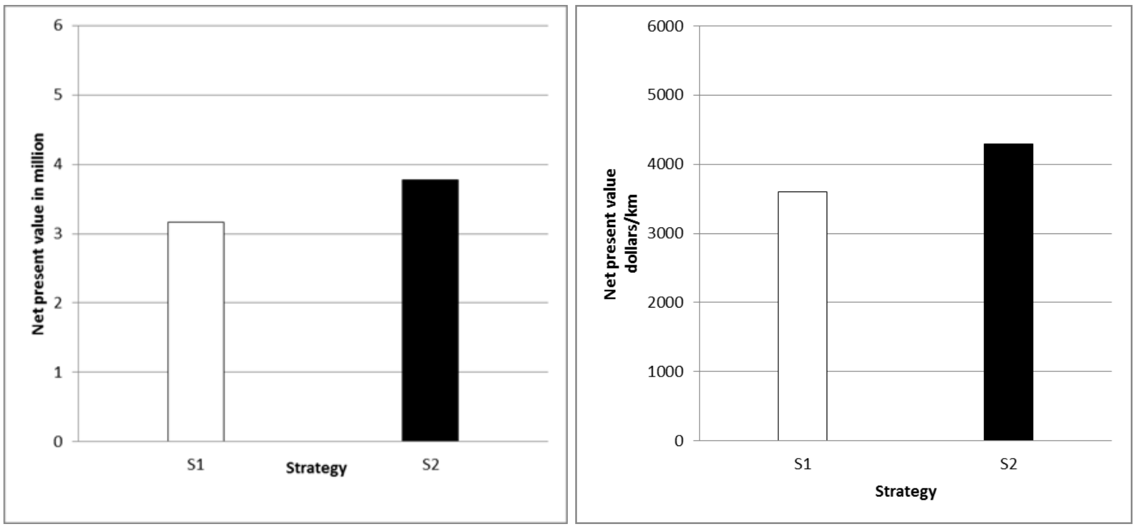
Figure 6-2. Agency cost by ADT



S_1: Without routing, S_2: With routing

Figure 6-3. Capital cost by ADT

Net present value is defined as the present value of the future cash receipts from the investment. From the simulation it is evident that the net present value of routing configuration is 18% higher compared with non-routing configuration based on 25 year analysis period. Figure 6-4 presents the net present value.

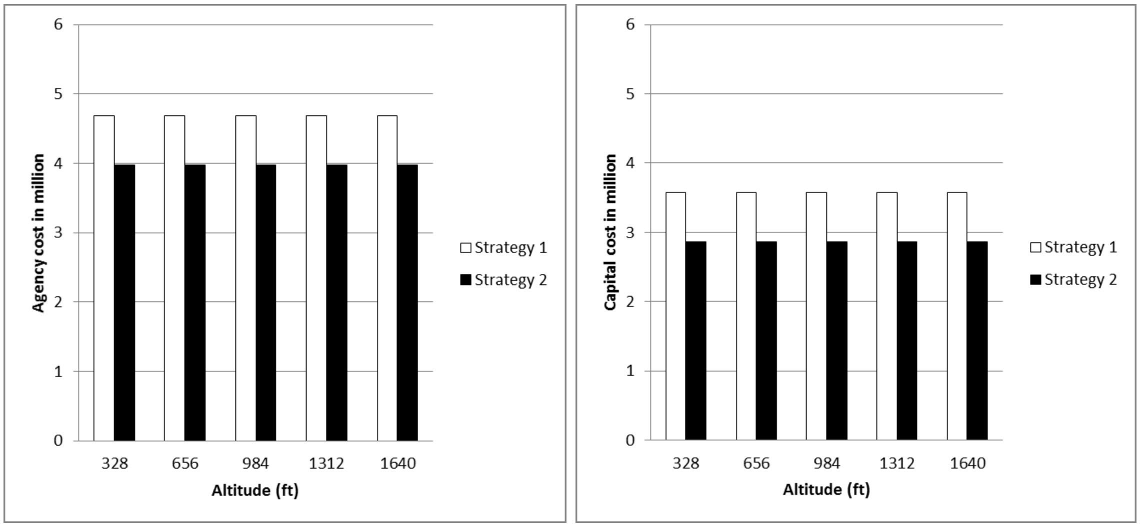


S_1: Without routing, S_2: With routing

Figure 6-4. Net present value by ADT

<u>Altitude analysis</u>

Altitude was defined as the mean elevation of the road section above the mean sea level. The research team varied the altitude from 100 to 500 meter but did not find any significant change in the cost. According to HDM-III this value has no significant effect on the results. Figure 6-5 and 6-6 illustrated the results.



S_1: Without routing, S_2: With routing

Figure 6-5. Agency cost and capital cost by altitude

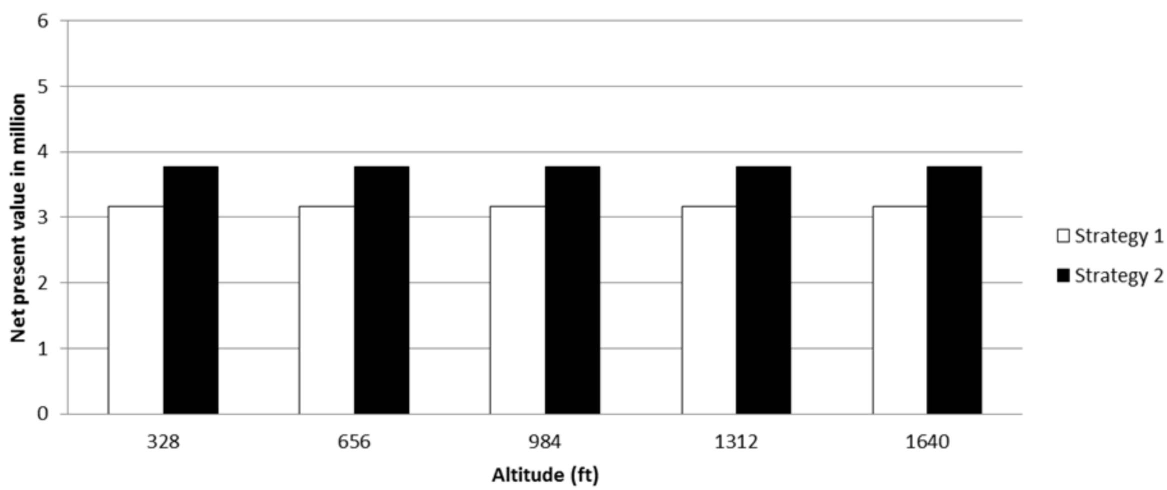


Figure 6-6. Net present value by Altitude

<u>Road length analysis</u>

Road length was varied from 100 to 500 kilometer to find out its effect on overall cost in terms of agency cost, capital cost and net present value. It follows the same trend with the findings of ADT. The road length has a significant effect on net present value. With routing configuration, agency cost is reduced to 14% compared to non-routing configuration over a 25 year period. Also from the simulation it is evident that the capital cost could be saved approximately 19% with routing configuration. Figure 6-7 presents the agency and capital cost with the variation of road length.

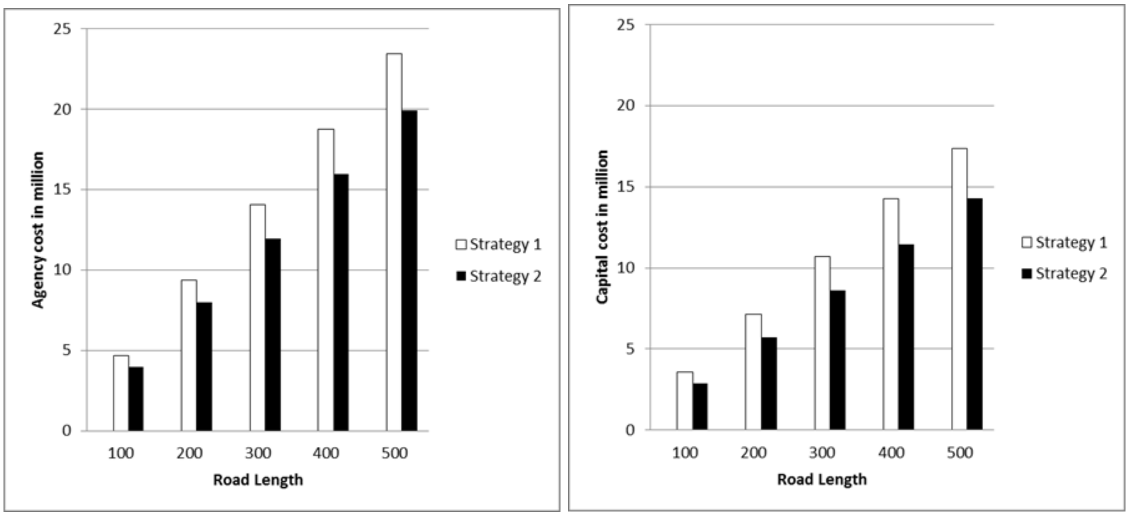


Figure 6-7. Agency cost and capital cost by road length

Road length has a vital effect on net present value. The net present value increases with the addition of the road length maintaining the savings up to 19% with routing configuration. It is obvious that if the road length goes increasing, there could be maintenance with routing configuration resulting more savings. Figure 6-8 shows the net present value according to the change in road length.

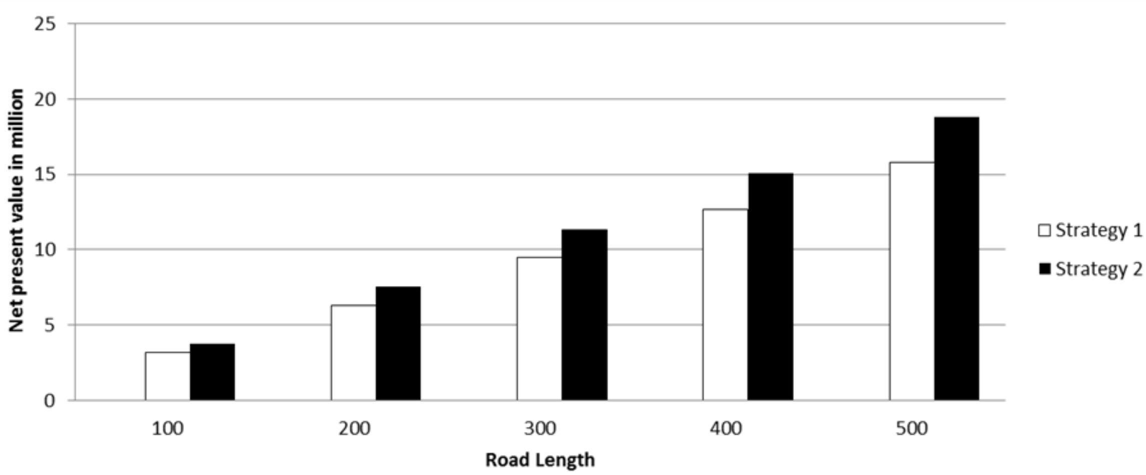


Figure 6-8. Net present value by road length

Cost Effective Strategy with the Increase of Unit cost due to Routing

Tables 6-2~6-4 present the total agency cost, capital cost and net present value for different interval years with the increase of financial cost while performing maintenance with routing.

Table 6-2. Agency cost for each interval year with the increase in unit cost due to routing

Cost Increase (%)	Financial cost	With routing (Resealing interval years)					
		3 years	4 years	5 years	6 years	7 years	8 years
0	4.00	6.46	4.89	3.98	3.34	2.85	2.94
10	4.40	7.80	5.28	4.27	3.57	3.03	3.09
20	4.80	7.53	5.65	4.55	3.78	3.20	3.24
25	***5.00***	7.80	5.83	***4.69***	3.89	3.29	3.31
30	5.20	8.08	6.03	4.84	4.01	3.38	3.39
40	5.60	8.60	6.40	5.12	4.23	3.55	3.53
50	6.00	9.15	6.79	5.41	4.46	3.73	3.68
60	6.40	9.67	7.16	5.70	4.67	3.90	3.82
61	***6.44***	9.72	7.19	5.72	***4.69***	3.91	3.84
70	6.80	10.22	7.54	5.99	4.90	4.07	3.97
80	7.20	10.74	7.91	6.27	5.12	4.24	4.12
90	7.60	11.33	8.33	6.56	5.34	4.42	4.27
100	8.00	11.81	8.67	6.84	5.56	4.59	4.41
105	***8.20***	12.08	8.85	6.98	5.67	***4.68***	4.48
106	8.24	12.14	8.90	7.01	5.70	4.70	4.50
110	8.40	12.36	9.05	7.13	5.79	4.77	4.56
119	***8.76***	12.84	9.39	7.39	5.99	4.92	***4.69***
130	9.20	13.42	9.81	7.70	6.23	5.12	4.85
140	9.60	13.95	10.18	7.99	6.45	5.29	5.00
144	9.76	14.17	10.33	8.10	6.54	5.36	5.06

Table 6-3. Capital cost for each interval year with the increase in unit cost due to routing

Cost Increase (%)	Financial cost	With routing (Resealing interval years)					
		3 years	4 years	5 years	6 years	7 years	8 years
0	4.00	6.35	3.78	2.86	2.22	1.74	1.47
10	4.40	5.89	4.16	3.15	2.45	1.91	1.62
20	4.80	6.42	4.53	3.44	2.67	2.09	1.76
25	***5.00***	6.68	4.72	***3.58***	2.78	2.17	1.83
30	5.20	6.96	4.91	3.73	2.89	2.26	1.91
40	5.60	7.49	5.29	4.01	3.11	2.43	2.05
50	6.00	8.03	5.67	4.30	3.34	2.61	2.20
60	6.40	8.56	6.04	4.58	3.56	2.78	2.35
61	***6.44***	8.60	6.08	4.61	***3.58***	2.80	2.36
70	6.80	9.10	6.43	4.87	3.78	2.96	2.50
80	7.20	9.63	6.80	5.15	4.00	3.31	2.64
90	7.60	10.22	7.21	5.44	4.23	3.30	2.79
100	8.00	10.70	7.55	5.73	4.45	3.48	2.94
105	8.20	10.96	7.74	5.87	4.56	3.56	3.01
106	***8.24***	11.02	7.78	5.90	4.58	***3.58***	3.02
110	8.40	11.24	7.94	6.02	4.67	3.65	3.08
119	8.76	11.72	8.28	6.27	4.87	3.81	3.22
130	9.20	12.31	8.69	6.59	5.12	4.00	3.38
140	9.60	12.84	9.06	6.87	5.34	4.17	3.52
144	***9.76***	13.05	9.22	6.99	5.43	4.24	***3.58***

Table 6-4. Net present value for each interval years with the increase in unit cost due to routing

Cost Increase (%)	Financial cost	With routing (Resealing interval years)					
		3 years	4 years	5 years	6 years	7 years	8 years
0	4.00	3.17	4.74	5.65	6.29	6.77	0.52
10	4.40	3.49	5.22	6.22	6.93	7.46	1.24
20	4.80	3.80	5.68	6.78	7.55	8.13	1.93
25	5.00	3.95	5.92	7.06	7.86	8.46	2.28
30	5.20	4.12	6.17	7.35	8.18	8.81	2.65
40	5.60	4.43	6.63	7.91	8.80	9.48	3.34
50	6.00	4.75	7.11	8.48	9.44	10.17	4.06
60	6.40	5.06	7.58	9.04	10.06	10.84	4.75
61	6.44	5.09	7.62	9.09	10.12	10.89	4.81
70	6.80	5.38	8.06	9.61	10.70	11.52	5.47
80	7.20	5.70	8.53	10.17	11.32	12.19	6.16
90	7.60	6.05	9.05	10.74	11.98	12.88	6.88
100	8.00	6.33	9.47	11.30	12.58	13.55	7.57
105	8.20	6.49	9.71	11.58	12.89	13.88	7.92
106	8.24	6.52	9.76	11.65	12.96	13.96	8.00
110	8.40	6.65	9.95	11.87	13.22	14.23	8.28
119	8.76	6.93	10.38	12.38	13.78	14.84	8.92
130	9.20	7.28	10.90	13.00	14.47	15.59	9.69
140	9.60	7.60	11.37	13.50	15.09	16.26	10.39
144	9.76	7.72	11.56	13.79	15.35	16.53	10.67

The percentage increase in cost for routing varied from 0 to 144 percent to find out its effect on overall cost in terms of agency cost, capital cost and net present value for different interval years (3~8 years). As it is mentioned earlier that agency and capital costs for routing configuration is less than non-routing configuration because of its longer service periods. So simulations have been run to observe how much percentage increase in financial cost with routing configuration exceed the total cost of non-routing configuration for each particular year in terms of agency and capital cost. When the total agency or capital cost for a particular year intersects with the non-routing configuration total cost due to the increase in financial cost for performing routing, that particular year is considered as the cost effective time for that particular percentage increase in cost due to routing. Figure 6-9 illustrates this concept for agency cost.

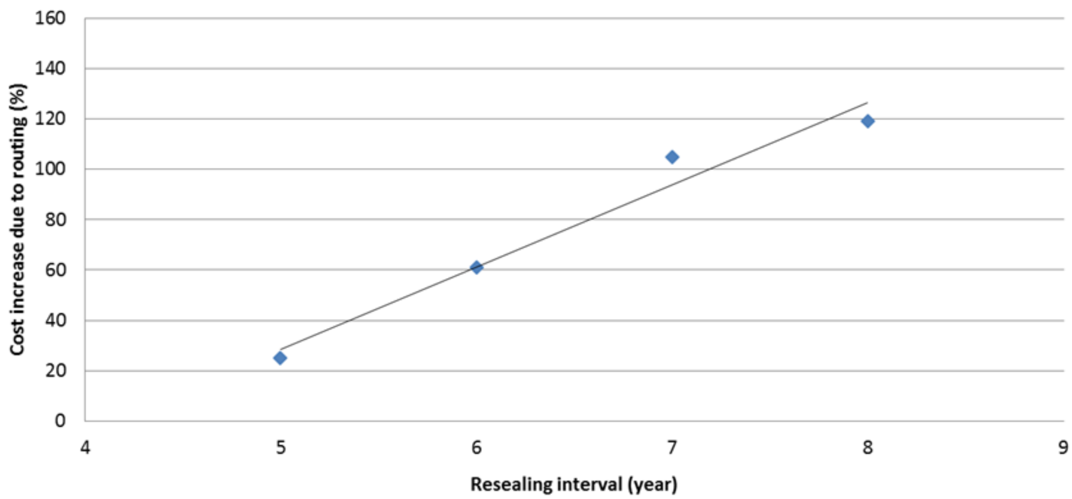


Figure 6-9. Selection of cost effective strategy for routing in terms of agency cost

The straight line points out the selection of appropriate cost effective strategy with the percentage increase of unit cost due to routing. It was found that the total cost for resealing interval periods of 3 and 4 years with routing configuration was much higher compared to without routing configuration resulting no intersection. However, for the rest of the longer interval periods the total cost for performing maintenance with routing was less than without routing configuration. When the cost of performing routing is increased by 25 percent, 5 years interval periods could be considered as cost effective before doing next routine maintenance. The interval periods of 6, 7 and 8 years can be taken into account for evaluating the cost effectiveness of performing routing if the cost is increased by 60%, 105% and 119%, respectively.

Figure 6-10 indicates the line for evaluating the cost effectiveness strategy for performing routing in terms of capital cost. The trend for evaluating the cost effective strategy for routing in terms of capital cost is very similar to the agency cost. However, for the capital cost the strategy of interval time of 8 years is cost effective when the cost of routing is increased by 144%.

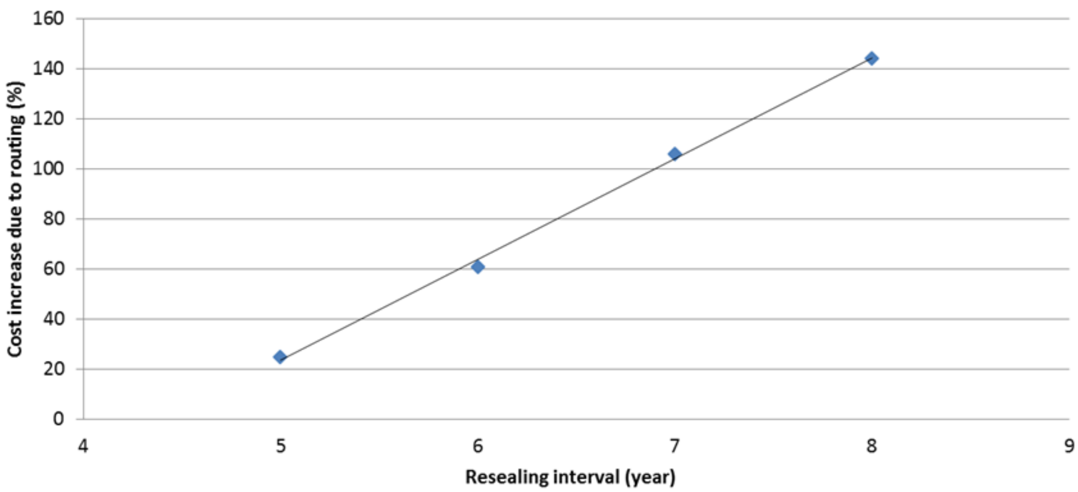


Figure 6-10. Selection of cost effective strategy for routing in terms of capital cost

Summary and Conclusions

A pavement deterioration model HDM-III has been used to evaluate the best cost effective maintenance in between routing (crack sealing) and non-routing (crack filling) configurations of crack sealing. These two configurations of crack sealing used as two maintenance strategies in HDM-III and economic analysis between these two strategies were performed in terms of agency cost, capital cost and net present value over a 25 year analysis period based upon ADT, altitude and road length. Also, simulations have been performed to select the cost effective strategy with the increase of unit cost due to routing. Overall based on the data analysis and the simulations run by the HDM-III modelling program, the following findings were drawn in this study:

1) It is more expensive for the agency to do maintenance with crack filling over a long period of time compared to crack sealing.
2) It has been found that agency cost in terms of ADT for crack sealing is approximately 15% less than crack filling. Similar trend has been noticed

for road length where agency cost can be reduced by 14% with crack sealing.

3) From the simulation it is evident that capital cost in terms of ADT and road length with crack sealing maintenance can be saved by 24% and 19%, respectively.

4) According to HDM-III analysis, there is no significant difference between these two pavement treatments based upon altitude. However, the net present value with crack sealing treatment after a 25 year analysis period is higher for ADT and road length compared to crack filling by 18% and 19%, respectively.

5) When the unit cost for performing routing is increased by 25 percent, the interval periods of 5 years could be considered as cost effective in terms of agency and capital cost before doing the next routine maintenance.

6) The analysis of data obtained from the simulations of HDM-III modeling needs to be examined by field data in terms of durability of the pavement after getting routine maintenance from crack sealing and filling. HDM program has the potential to find out the cost effectiveness of other pavement maintenance strategies in order to select the best strategy to reduce the cost of agency.

Cost-effectiveness of Crack Treatment Analyzed by Field Cost Input

One of the another objective of this chapter is to find out the initial cost and long term cost effectiveness between crack sealing and filling using real field cost data. Four test sites were selected based upon several criteria, including location, Average Annual Daily Traffic (AADT), material and conditions (pavement condition, drainage etc) in Texas. Each potential cost factors (sealing time, labor, material, equipment, traffic, etc) and all the cost inputs were identified and calculated in order to determine the best cost effective treatment.

Methodology

<u>Road length analysis</u>

Installation took place at four test locations under a variety of conditions in Texas. Selected test sections represented various environmental conditions (altitude and rainfall), material condition, Average daily traffic (ADT) and pavement conditions. These test sites were:

- Fort Worth
- Abilene (Big Spring)
- Brownwood
- Corpus Christi

The length and width of the designated cracks for crack filling were measured using slide calipers. Several cracks were measured and the the average length and width of those cracks were calculated. The average configuration profile for crack filling was considered 1/8 by 1/4 [W(inch) x D(inch)]. Routing was done on a 1x1 profile or 1/2 by 1/2. In order to observe the cost effectiveness with a small reservoir for crack sealing treatment, a 3/8 by 3/8 configuration was added. The cost effectiveness between these two types of methods of crack sealing was also investigated.

<u>Initial cost analysis</u>

Identification of total time of sealing

The total time of performing sealing depends on several criteria, which includes: traffic control set up, traffic control removal, waiting period for starting sealing before cleaning cracks and routing, and curing period. Traffic control is one of the most important practices during the implementation of crack treatments; this practice enhances the safety of all workers. As mentioned earlier, traffic control was provided by TxDOT. The setup time for traffic control was recorded on average approximately at 30 minutes in the field for all test sites. After the construction, the traffic control removal time was measured. For the construction using crack filling, selection of the appropriate cracks was considered as the first task. The next task was to clean the crack and then fill the cracks with sealant material. In the field, all tasks were done simultaneously. After designating the cracks, the cleaning crew started to clean the cracks and the sealant crew followed after 10 minutes to put the sealant materials into the clean cracks. The reason behind allowing a 10 minute interval period was to avoid overlapping between these two tasks. As a result, both tasks were done simultaneously and the sealant crew had sufficient cracks to seal before reaching the point where the cleaning crew was doing the work. For the construction using crack sealing, the additional step of routing before cleaning the cracks was performed. For this method, 20 minutes was allowed as the waiting period before starting the sealing of the cracks.

As appropriate curing time was provided after sealing the cracks and before measurements were taken. A reasonable amount of time was allowed for curing after completion of sealing before opening the road to traffic. The amount of time to cure the sealant material was recorded as on average approximately 15 minutes in the field for all test sites. The total time for sealing the cracks was calculated by subtracting the times for traffic setup, traffic removal, waiting period before starting sealing and cure time from an 8 hour working day for all test sites.

Length sealed per day

The length sealed per hour was calculated by the length of sealed cracks divided by the total sealing time at each test site. This result was multiplied by the prospective total sealing time performed in an 8 hour working day.

Material cost per day

As mentioned earlier, the reservoir area for crack filling and sealing are different and depending on the volume of reservoir the material application rate would be different for each treatment type. The volume of the reservoir was calculated in a one linear foot of crack. The gross application rate of material in one linear foot of crack was calculated by multiplying the volume of reservoir by the unit weight of hot pour sealant materials. The net application rate of material was calculated by multiplying the gross application rate of material by 15% waste. The cost of the material per day was calculated by multiplying the length sealed per day by the actual amount of material used per linear foot for sealing at each test section and multiplying this by the material cost per unit.

Traffic control cost

The cost for the overall traffic control equipment (arrow board, cone hauling truck, pickup truck, etc.) at each construction site was provided by TxDOT.

Crew cost

Four personnel were included for the crack filling operations: i) crack cleaning, ii) crack sealing, iii) squeegeed flush to the surface of the road and iv) hot pour sealant equipment driver. For crack sealing, one additional personnel was required for routing the crack. The crew cost per hour was provided by Crafco.

Air compressor, router and hot melt equipment

The cost per day for the air compressor, router and hot melt equipment was provided by Crafco.

Total cost and unit cost

The total cost per day was calculated by adding together the material, traffic control, crew, and equipment cost per day. The unit cost in dollars per linear foot was calculated by dividing the total cost per day by the total length of sealing work.

Average annual cost (AAC)

The AAC was calculated based on the explanations given in SHRP-H-348 “Materials and Procedures for Sealing and Filling Cracks in Asphalt Surfaced Pavements”. The user delay cost and interest rate were considered while calculating the AAC. AAC values were calculated based on a 5 percent interest rate and user delay cost of $2,000 per day. The calculated initial cost for this project was taken as an input for the AAC.

Life Cycle Cost Analysis (LCCA)

Survey

A survey of crack sealing and crack filling procedures was developed and distributed in Texas. The response was received and analyzed. Texas does not currently require routing, but decides on a case-by-case basis whether it is needed. Questionnaires were sent to 25 Districts, with response received from 19. In Texas, no Districts practice routing however one of the responses (Amarillo) provided that they have performed routing in the past but left it due to time consumption and equipment issues. Durability of the crack sealant application varied from 3-5 years around the state. However, 40 percent of the Districts do not have field evaluation methods for measuring the crack sealing performance. Of those Districts that responded, six stated that blowing out the debris from cracks with air has seemed to get them clean enough to seal and ensured good success with the current method. Five Districts responded that crack sealing with routing is a costly practice. Other Districts mentioned that this practice is uncommon and do not have proper guidelines. Also, one District stated no idea about its benefit.

Decker (2014) conducted a survey on 157 individual from 28 state DOTs, 106 countries, 3 cities, 2 Federal Highway Administration (FHWA), 1 Canadian province, 2 U.S. contractors and 1 contractor from New Zealand. An estimate of the typical life span for crack sealing and crack filling on both major and minor roads was requested. It was concluded that the majority of the respondents think crack sealing on both major and minor roads can perform for 5-10 years, but that crack filling will only last 1-4 years. Yildirim et al. (2006) reported that crack sealing without a routing method using hot-pour sealant materials has a typical life cycle of 3-5 years. Rajagopal (2011) reported that their prediction model indicated a life span of 3.6 years using the crack filling method. According to the literature review and survey from the Texas Districts, it was considered that the pavement would perform with crack filling for 3 years and crack sealing for 5 years.

Strategy

The determination of the long term cost effectiveness between crack sealing and crack filling was based upon two categories:

i) Initial cost, and

ii) Durability of pavement after the two treatment type

As has been previously stated that the initial cost of crack sealing is more costly compared to crack filling, the service period is longer with crack sealing compared to crack filling. Initial cost per linear foot measured for crack sealing and crack filling was used as an input in the LCCA for both treatment types. A 35-year analysis period was established to calculate the long term cost effectiveness between these two treatment types. A new asphalt overlay was considered to be placed after the service period of each treatment type. For example, the new overlay would be placed after three years and five years of service period for crack filling and crack sealing, respectively. The overlay cost of $ 27.38 (including all associated cost regarding freight and material) per linear foot used for the input in LCCA. In order to make the calculation simple, the interest rate, inflation rate and user delay costs were neglected. Also, depending upon the economic climate, the value may be very difficult to estimate for any time in the future past a 35-year analysis period.

Results and Discussions

The key objective of this study was to determine the short term and long term cost effectiveness of crack sealing and crack filling. To determine the objective, the cost analysis was based on the comparison of all cost aspects regarding the implemented crack treatments on four highways in Texas. Each potential cost input for the construction of both treatments was recorded and analyzed to determine the initial, average annual and life cycle cost.

<u>Initial cost analysis</u>

The cost factors for each task during the construction of crack sealing and crack filling were determined and data used for analysis subdivided into six categories: total time of sealing, length of sealed cracks, material cost, traffic control, number of crew personnel, and sealing equipment. In order to show the method of calculating these costs, one sample calculation from crack filling and another from crack sealing (3/8 x 3/8) used to illustrate the calculation of costs.

Initial cost calculation (Crack filling)

Total time of Sealing:

Traffic control setup = 30 minutes/0.5 hrs

Traffic control removal = 30 minutes/0.5 hrs

Waiting period for starting sealing before cleaning = 10 minutes/0.17 hrs

Curing period = 15 minutes/0.25 hrs

Work day = 8 hrs

Filling time = 8 – 0.5 – 0.5 – 0.17 – 0.25 = 6.58 hrs

Length sealed per day:

Length of the sealed cracks at site = 978 linear feet

Sealing time at site = 25 minutes

Length sealed per day = (978/25) x 60 x 6.58 = 15444.58 per day

Material cost per day:

Length sealed per day = 15444.58 lf

Cross sectional area of reservoir = (0.12 in x 0.25 in) = 0.03 in^2

Volume of reservoir (1 lin ft of crack) = 1ft x (0.03/144 ft^2) = 0.000208 ft^3

Gross application rate (no waste) = 73.31 (lb/ft^3) x 0.000208 = 0.0152 lb/lin ft of crack

Net application rate (15% waste) = 1.15 x 0.0152 = 0.01748 lb/lin ft of crack

Material cost = $0.68/lb

Material cost per day = 15444.58 x 0.01748 x 0.68 = $183.6

Traffic control cost per day = $1000

Crew cost:

No. of personnel required = 4

Cost per hour = $22

Total crew cost = $88 x 8 =704

Truck + Compressor per day = $250

Hot Melt Equipment per day = $380

Total cost = 183.6+1000+704+250+380 = $2517

Unit cost = $0.16 per foot

Initial cost calculation (Crack sealing: 3/8" x 3/8")

Total time of sealing:

Traffic control setup = 30 minutes/0.5 hrs

Traffic control removal = 30 minutes/0.5 hrs

Waiting period for starting sealing before cleaning & routing = 20 minutes/0.33 hrs

Curing period = 15 minutes/0.25 hrs

Work day = 8 hrs

Filling time = 8 – 0.5 – 0.5 – 0.33 – 0.25 = 6.42 hrs

Length sealed per day:

Length of the sealed cracks at site = 978 linear feet

Sealing time at site = 25 minutes

Length sealed per day = (978/25) x 60 x 6.42 = 15069.02 per day

Material cost per day:

Length sealed per day = 15069.02 lf

Cross sectional area of reservoir = (0.375 in x 0.375 in) = 0.140625 in^2

Volume of reservoir (1 lin ft of crack) = 1ft x (0.140625/144 ft^2) = 0.000977 ft^3

Gross application rate (no waste) = 73.31 (lb/ft^3) x 0.000977 = 0.0716 lb/lin ft of crack

Net application rate (15% waste) = 1.15 x 0.0716 = 0.08234 lb/lin ft of crack

Material cost = $0.68/lb

Material cost per day = 15069.02 x 0.08234 x 0.68 = $843.73

Traffic control cost per day = $1000

Crew cost:

No. of personnel required = 5

Cost per hour = $22

Total crew cost = $110 x 8 =880

Truck + Compressor per day = $250

Hot Melt Equipment per day = \$380

Router rent per day = \$100

Total cost = 843.73+1000+880+250+380+100 = \$3453

Unit cost = \$0.23 per foot

Percentage increasing with crack sealing = (3453 - 2517)/2517 x 100 = 37.18%

Based on the aforementioned calculation procedure, the construction cost of crack sealing and crack filling for each test section was estimated. As expected the initial cost of crack sealing is higher compared to crack filling. In between the two configurations of crack sealing, the small reservoir has less construction cost. Figure 6-11 presents the total construction cost at each test section.

It is worth to note that the research team considered the different amount of treated crack length for each test site in order to observe the influential cost factors behind the construction of both treatment types. Table 6-5 presents the treated crack length at each test site.

Table 6-5 Total amount of treated crack length at each test site

Test Sites	Big Spring	Fort Worth	Brownwood	Corpus Christi
Treated crack length (linear feet)	978	633	775	723

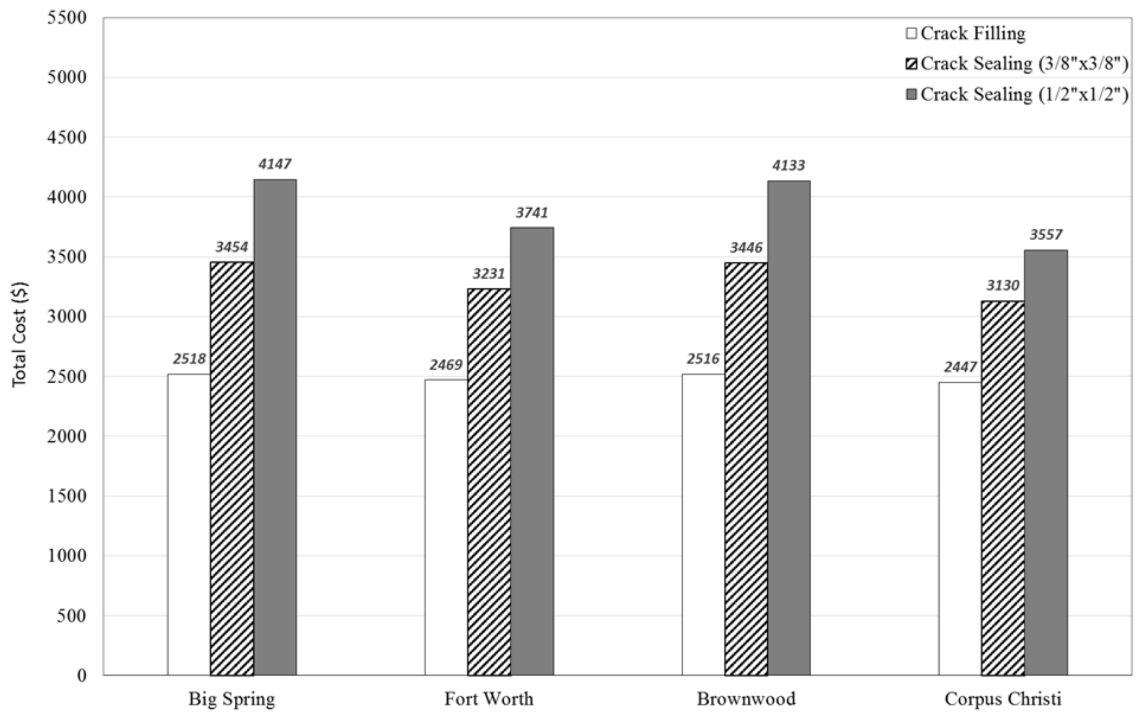


Figure 6-11. Initial cost for crack filling and sealing at each test site

It can be observed that the difference of total construction cost among the test sites was mainly due to the use of amount of materials and labor cost during construction which depends upon the sealing time spent at site by crew personnel and treated crack length per day. The total labor cost of crack filling and sealing treatment calculated $704 and $880 respectively, per day. From the calculation, it is evident that the amount of material has the most significant effect on the high initial construction cost of crack sealing (1/2 x 1/2) because of its bigger cross-sectional area compared to crack filling. However, it is found that for crack filling and routing configuration of 3/8 x 3/8, labor cost is more significant cost factor compared to material cost. In general, for all test sites 4.5 and 8.4 times more material used compared to crack filling with the routing configuration of 3/8 x 3/8 and 1/2 x 1/2, respectively. Figure 6-12 illustrates the material cost at each test site for two types of treatment.

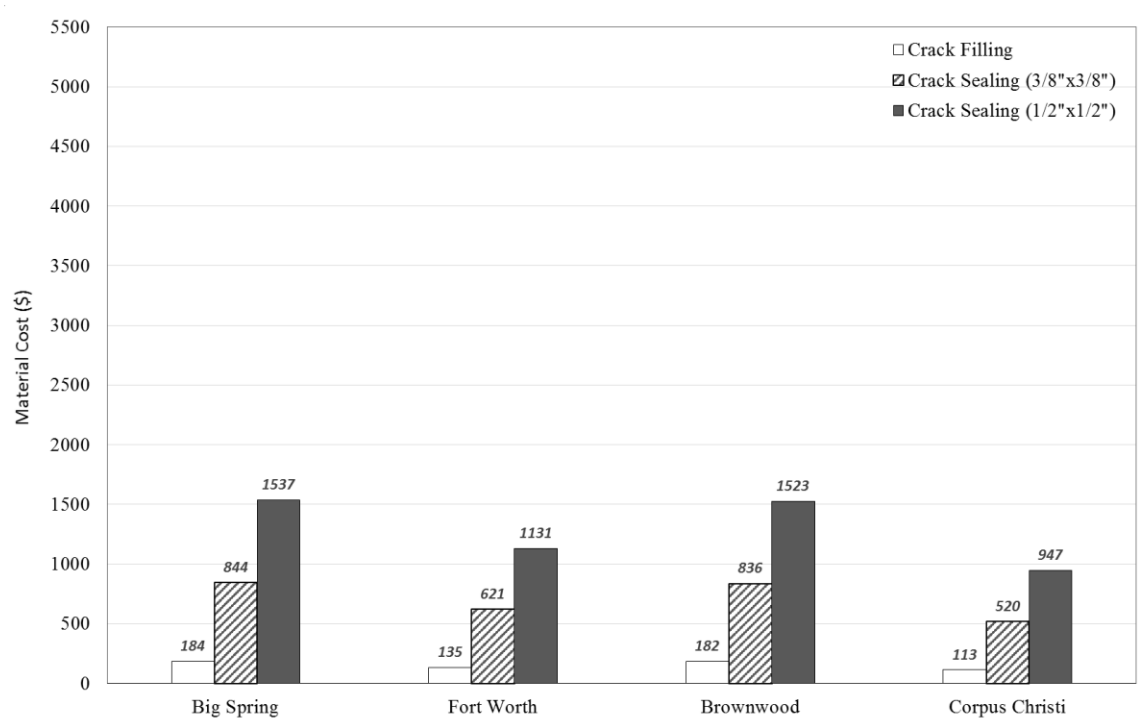


Figure 6-12. Material cost for crack filling and sealing at each test site

The unit cost in dollars per linear feet was calculated by dividing the total cost per day by the length of sealing work. Figure 6-13 illustrates the initial construction cost per linear feet for crack filling and sealing at each test site. As expected, the construction of crack sealing treatment is expensive due to the use of extra material, labor and equipment. Figure 6-14 presents the percentage cost increase with the two routing configurations of crack sealing at each test site.

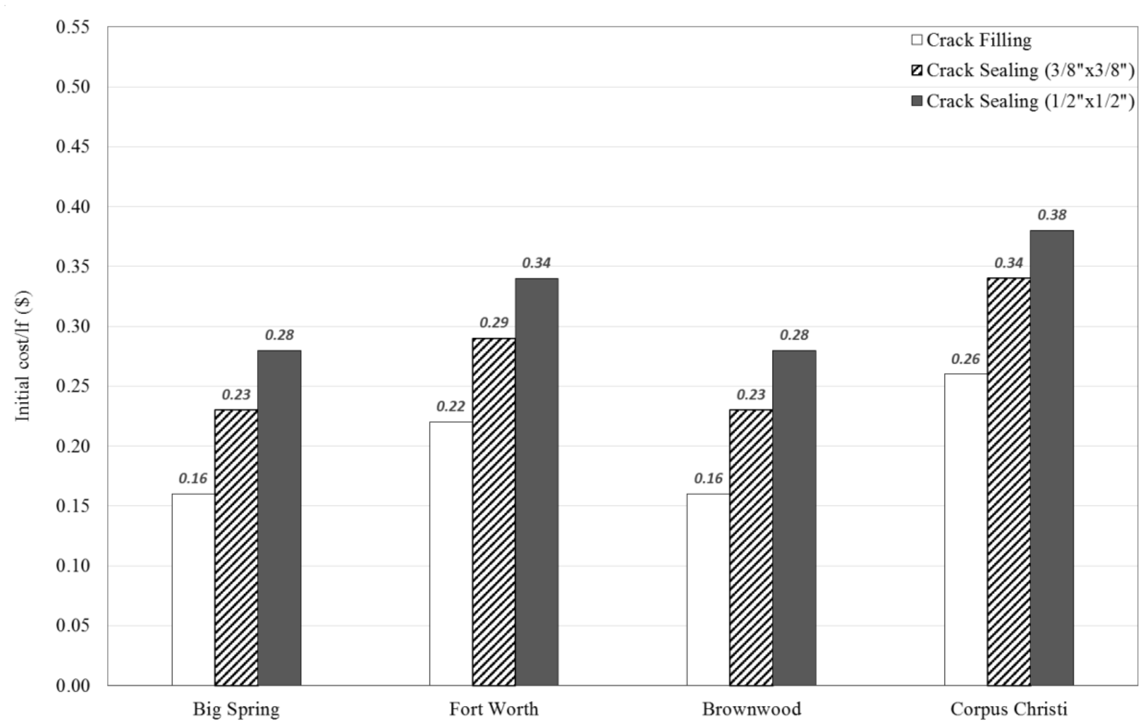


Figure 6-13. Initial cost per linear feet for crack filling and sealing at each test site

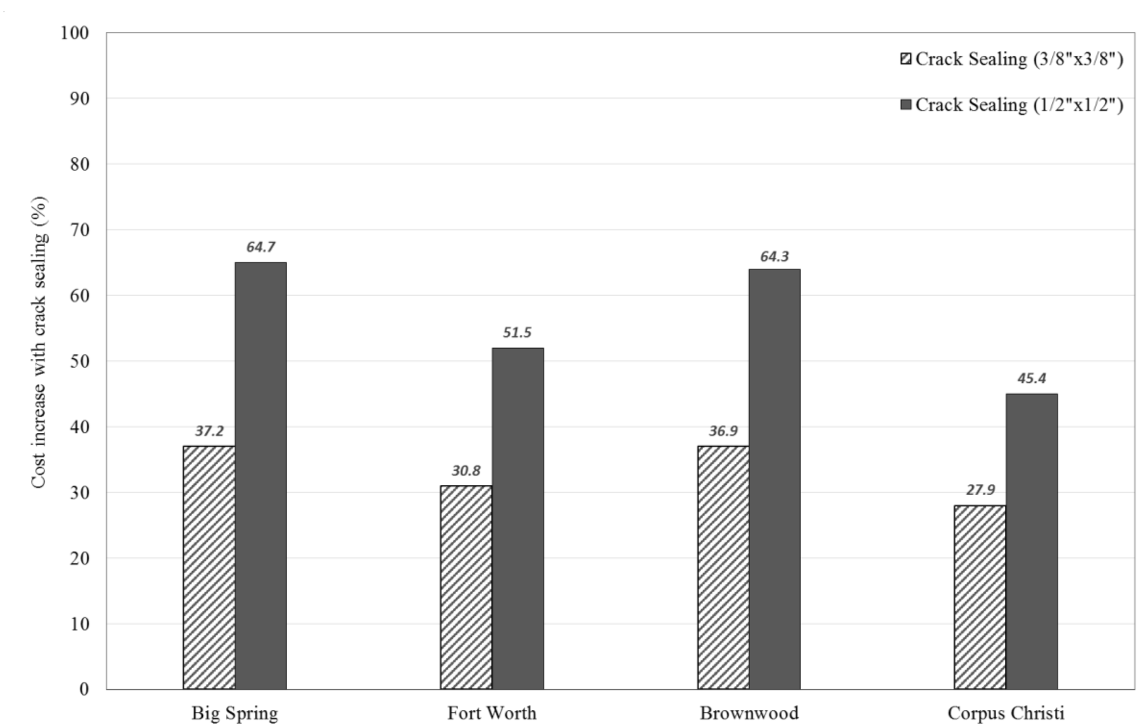


Figure 6-14. Cost increase with crack sealing at each test site

It has shown that the initial cost of agency could be approximately 27.9% to 37.2% (on an average 33%) higher with 3/8 x 3/8 and 51.5% to 64.7% (on an average 56%) higher with 1/2 x 1/2 routing configuration of crack sealing compared to crack filling depending upon the change of test site.

As a result, the agency can have less initial cost with small reservoir of crack sealing. Table 6-6 illustrates the initial cost reduction with 3/8 x 3/8 configuration compared to the 1/2 x 1/2 configuration of crack sealing. It is evident that the agency cost could be saved by approximately 12% to 17% (on an average 15%) with 3/8 x 3/8 configuration compared to 1/2 x 1/2 routed channel.

Table 6-6 Initial cost reduction with small reservoir (3/8" x 3/8")

Site	3/8" x 3/8" Total cost ($)	1/2" x 1/2" Total cost ($)	Percentage reduction (%)
Big Spring	3453.73	4146.80	16.71
Fort Worth	3230.56	3740.49	13.63
Brownwood	3445.75	4132.51	16.62
Corpus Christi	3129.79	3556.90	12.01

<u>AAC analysis</u>

As mentioned earlier AAC was calculated based on the instructions given in SHRP-H-348. The interest rate of 5% and user delay cost of $2000 were considered for the calculation of AAC. The cost factors obtained from this project were taken as an input for AAC. Table 6-7 presents the sample calculation of AAC based on the cost data calculated for Big Spring test site. Figure 6-15 shows the calculated AAC of crack sealing and filling at each test site. It has shown that crack sealing is more cost effective than crack filling based on the calculated AAC.

Table 6-7 Sample calculation of costs for the analysis of AAC in Big Spring test site

Cost parameter	Crack filling	Crack sealing (3/8" x 3/8")	Crack sealing (1/2" x 1/2")
A. Cost of purchasing and shipping material	0.68/lb	0.68/lb	0.68/lb
B. Net application rate	0.02 lb/lin ft	0.08 lb/lin ft	0.15 lb/lin ft
C. Placement cost	1718/day	1840/day	1840/day
D. Production rate	15445 lin ft/day	15069 lin ft/day	15069 lin ft/day
E. User delay cost	2000/day	2000/day	2000/day
F. Total installation cost F= (AxB) + (C/D) + (E/D)	0.29/lin ft	0.36/lin ft	0.41/lin ft
G. Interest rate	5.0 percent	5.0 percent	5.0 percent
H. Estimated service life	3 years	5 years	5 years
I. Average annual cost	0.11/lin ft	0.08/lin ft	0.09/lin ft

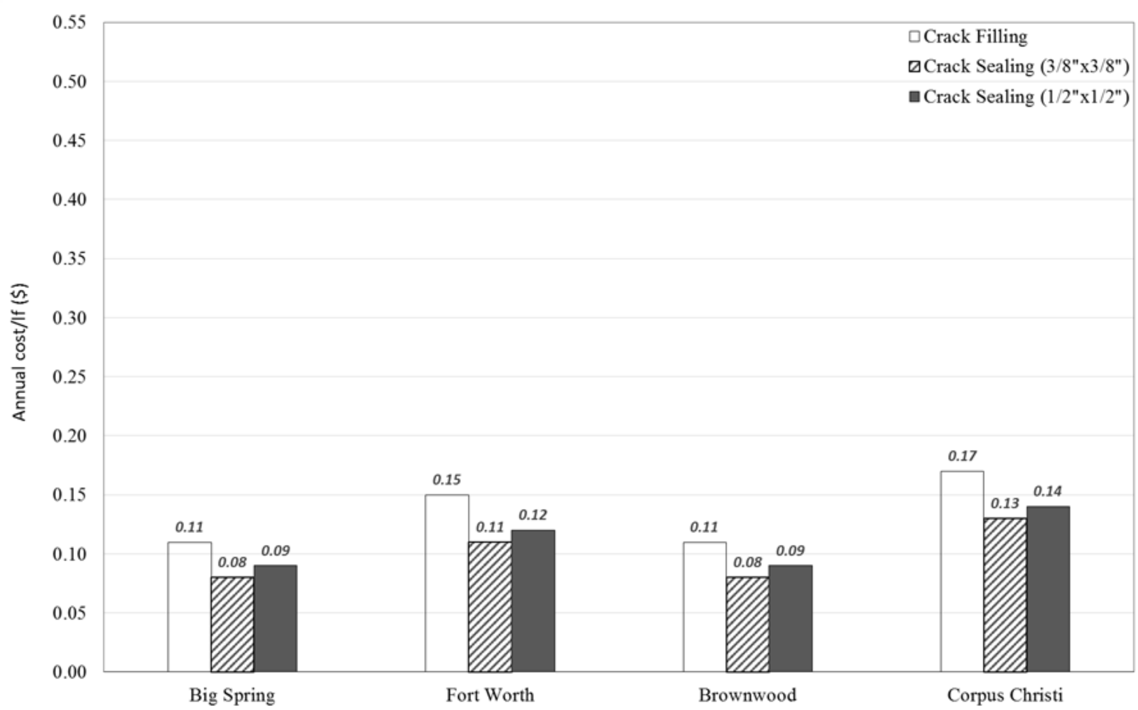


Figure 6-15. AAC per linear feet for crack filling and sealing at each test site

LCCA Analysis

In order to find out the long term cost effectiveness treatment between crack sealing and filling a 35 year analysis period was established. It was calculated based on the service life information collected from the TxDOT survey and existing literature review. For crack filling and sealing the research team considered a service period of 3 years and 5 years, respectively. To identify the long term costs between these two treatment types, all cost factors were calculated in an excel sheet using the initial construction and overlay cost per linear feet with no rounding. Figure 6-16 illustrates the LCCA cost calculation sample for Big Spring test site. At the beginning a new asphalt mat has been placed. After two years linear cracks appeared on the surface of the pavement. For those linear cracks, crack filling and crack sealing treatment has been given. Crack filling and crack sealing treatment will last for 3 years and 5 years, respectively. With crack filling treatment a new asphalt mat will be again placed after 5 years and with crack sealing after 7 years. This is the reason behind the consideration of a 35 year analysis period to analyze the long term cost effectiveness between these two treatments. In between 35 years, resealing with crack filling treatment will be performed 5 times and with crack sealing 7 times. Table 6-8 presents the long term cost per linear feet associated with this two types of treatment. It is evident from the calculation that in between these two treatments crack sealing is the most appropriate long term cost effective treatment. Based upon the calculated long term cost at different test site, it can be deduced that on an average with crack sealing treatment an agency can save approximately 24% more than crack filling treatment.

	Crack Filling (Non-Routed)					Crack Sealing (Routed)				
	New Asphalt Mat	Crack Filling	Totals	Running Tota	Event Description	New Asphalt Mat	Crack Sealing	Totals	Running Tota	Event Description
Years	$ / LF	$ / LF	$ 220.16			$ / LF	$ / LF	$ 165.43		
0	$ 27.38		$ 27.38	$ 27.38	A new asphalt mat has been placed.	$ 27.38		$ 27.38	$ 27.38	A new asphalt mat has been placed.
1			$ -	$ 27.38				$ -	$ 27.38	
2		$ 0.16	$ 0.16	$ 27.54	A small crack appears and it is filled.		$ 0.23	$ 0.23	$ 27.61	A small crack appears and it is sealed.
3			$ -	$ 27.54				$ -	$ 27.61	
4			$ -	$ 27.54				$ -	$ 27.61	
5	$ 27.38		$ 27.38	$ 54.92	New overlay mat is placed.			$ -	$ 27.61	
6			$ -	$ 54.92				$ -	$ 27.61	
7		$ 0.16	$ 0.16	$ 55.08	A small crack appears and it is filled.	$ 27.38		$ 27.38	$ 54.99	New overlay mat is placed.
8			$ -	$ 55.08				$ -	$ 54.99	
9			$ -	$ 55.08			$ 0.23	$ 0.23	$ 55.22	A small crack appears and it is sealed.
10	$ 27.38		$ 27.38	$ 82.46	New overlay mat is placed.			$ -	$ 55.22	
11			$ -	$ 82.46				$ -	$ 55.22	
12		$ 0.16	$ 0.16	$ 82.62	A small crack appears and it is filled.			$ -	$ 55.22	
13			$ -	$ 82.62				$ -	$ 55.22	
14			$ -	$ 82.62		$ 27.38		$ 27.38	$ 82.60	New overlay mat is placed.
15	$ 27.38		$ 27.38	$ 110.00	New overlay mat is placed.			$ -	$ 82.60	
16			$ -	$ 110.00			$ 0.23	$ 0.23	$ 82.83	A small crack appears and it is sealed.
17		$ 0.16	$ 0.16	$ 110.16	A small crack appears and it is filled.			$ -	$ 82.83	
18			$ -	$ 110.16				$ -	$ 82.83	
19			$ -	$ 110.16				$ -	$ 82.83	
20	$ 27.38		$ 27.38	$ 137.54	New overlay mat is placed.			$ -	$ 82.83	
21			$ -	$ 137.54		$ 27.38		$ 27.38	$ 110.21	New overlay mat is placed.
22		$ 0.16	$ 0.16	$ 137.70	A small crack appears and it is filled.			$ -	$ 110.21	
23			$ -	$ 137.70			$ 0.23	$ 0.23	$ 110.44	A small crack appears and it is sealed.
24			$ -	$ 137.70				$ -	$ 110.44	
25	$ 27.38		$ 27.38	$ 165.08	New overlay mat is placed.			$ -	$ 110.44	
26			$ -	$ 165.08				$ -	$ 110.44	
27		$ 0.16	$ 0.16	$ 165.24	A small crack appears and it is filled.			$ -	$ 110.44	
28			$ -	$ 165.24		$ 27.38		$ 27.38	$ 137.82	New overlay mat is placed.
29			$ -	$ 165.24				$ -	$ 137.82	
30	$ 27.38		$ 27.38	$ 192.62	New overlay mat is placed.		$ 0.23	$ 0.23	$ 138.05	A small crack appears and it is sealed.
31			$ -	$ 192.62				$ -	$ 138.05	
32		$ 0.16	$ 0.16	$ 192.78	A small crack appears and it is filled.			$ -	$ 138.05	
33			$ -	$ 192.78				$ -	$ 138.05	
34			$ -	$ 192.78				$ -	$ 138.05	
35	$ 27.38		$ 27.38	$ 220.16	New overlay mat is placed.	$ 27.38		$ 27.38	$ 165.43	New overlay mat is placed.

Figure 6-16 LCCA cost calculation sample for Big Spring test site

Table 6-8 Long term cost effectiveness of crack filling and sealing

Site	3/8" x 3/8"			1/2" x 1/2"		
	Crack filling (cost/lf)	Crack Sealing (cost/lf)	Percentage reduction (%)	Crack filling (cost/lf)	Crack Sealing (cost/lf)	Percentage reduction (%)
Big Spring	220.16	165.43	24.86	220.16	165.68	24.75
Fort Worth	220.58	165.73	24.87	220.58	165.98	24.75
Brownwood	220.16	165.43	24.86	220.16	165.68	24.75
Corpus Christi	220.86	165.98	24.85	220.86	166.18	24.76

Summary and Conclusions

This study is conducted to evaluate cost effectiveness between crack filling and crack sealing treatments. Potential cost factors were identified, recorded and analyzed for both treatments to find out the initial, average annual and life cycle cost upon the data obtained from the four test sites in Texas. Based on the results of the study, the following conclusions can be drawn:

1) According to the response of 20 Texas districts and extensive literature review a typical asphalt pavement could stand for three years and five years with crack filling and crack sealing treatment, respectively.
2) The initial construction cost of crack sealing is higher compared to crack filling. Based on the results of four test sites, this cost could be 27.9% to 37.2% and 51.5% to 64.7% higher with 3/8 x 3/8 and 1/2 x 1/2 routing configuration, respectively. It is recommended to implement the small reservoir for crack sealing, if it can ensure the adequate durability. It is evident that initial cost could be reduced by on an average 15% with 3/8 x 3/8 configuration of crack sealing compared to 1/2 x 1/2 routed channel.
3) Material and labor cost has the most significant effect on the difference of higher initial construction cost between crack sealing and crack filling compared to other associated costs.
4) AAC cost calculation has shown that crack sealing is more cost effective than crack filling.
5) Based on the 35 year analysis period, the agency cost can be reduced by approximately 24% compared to crack filling.

This chapter (VI) includes a part of the following publications;

Mazumder, M., Kim, H. H., Lee, S.-J., Lee, M.S., "Cost effectiveness of crack treatment methods: A field study" *Journal of Traffic and Transportation Engineering*, https://doi.org/10.1016/j.jtte.2018.01.010 (March 2019).

Mazumder, M., Kim, H. H., Lee, S.-J., Lee, M. S., "Evaluation of Crack Treatment Methods Using HDM-III Modelling" *International Journal of Civil Engineering* (Accepted).

CHAPTER VII

ENVIRONMENTAL IMPACTS

Introduction

The purpose of the chapter is to assess the initial and long term environmental impact of three life cycle phases (material, construction and maintenance) of crack treatment (crack sealing and filling) methods in flexible pavement. The environmental burdens are quantified and compared between these two treatment types during the construction and over a 35 year analysis period. The environmental emission for each life cycle phase is quantified and compared. In order to achieve that objective a life cycle inventory is used and impact assessments are evaluated on eight impact categories. The raw material extraction, production, construction, transportation and service period are the main cumulative contributions to the overall environmental burdens. In addition to that another important sub-goal for the study is to come up with a feasible methodology for life cycle assessment of crack treatment and to observe the trends in the impact areas for each phase of crack treatment.

Scope and System Boundary

Bitumen is made in a hypothetical complex refinery and manufactured by straight run distillation crude oil. During this process the residue from the atmospheric distillation of crude oil is further distilled in a vacuum tower to produce paving grade bitumen. The study included the bitumen production chain, from raw material extraction and ending with a product delivery to a customer. It includes crude oil extraction, transport, production and storage. It excludes the use of water cooling and turbine use. Styrene butadiene styrene

(SBS) is used to produce the polymer modified bitumen with a content of 3.5%. The environmental burdens are quantified on three life cycle phases of crack treatment method. The scope and system boundary considered for the study is shown in Table 7-1.

Table 7-1. System boundaries of the study

Environmental impacts	
Included in the study	Not included in the study
Phase I : Material	
Energy, greenhouse gas (GHG) emissions, acidification, photo oxidant formation, human toxicity (air and water), eco toxicity (air and water), and eutrophication during production of bitumen and polymer modified bitumen.	• Land disruption • Noise emission • Traffic safety • Transportation of bitumen to plant
Phase II: Construction	
Energy, Greenhouse gas (GHG) emissions, acidification, photo oxidant formation, human toxicity (air and water), eco toxicity (air and water), and eutrophication during the construction of crack treatment methods.	• Noise emission • Traffic safety
Phase III: Maintenance	
Greenhouse gas (GHG) emissions, acidification, photo oxidant formation, human toxicity (air and water), eco toxicity (air and water) and eutrophication during maintenance	• Noise emission • Transportation of materials to site • Traffic safety

Life Cycle Phases

Crack treatment method has three life cycle phases which are:

i) Material production

ii) Construction of treatment

iii) Maintenance

The life cycle begins with bitumen being processed from the crude oil or natural sources. Polymer is added to the asphalt binder in order to make crack sealant material. Collected sealant material is transported to the construction site. Sealant material is placed on the selected crack and rubber squeegee used to make the sealant material flush to the surface so that it can provide a smooth surface to the drivers. Crack sealing is defined as using a router to create a reservoir or routed channel in a crack. After that the routed channel is filled with a sealant material. On the other hand, crack filling is defined as minor crack preparation, such as using an air gun to blow debris out of cracks, prior to installation of the sealant. There is no pavement removed with crack filling.

With crack sealing treatment, cracks are routed to a predefined geometry, cleaned and materials are placed into it in order to prevent the intrusion of water into the pavement surface through the upper surface. Routes are generally given with a width to depth ratio of one or greater than one that can enhance the sealant performance (Wang et al. 1993; Ketcham 1996; Khuri et al. 1992). Figure 7-1 illustrates different stages of the crack filling and sealing installation process. After the service period of crack treatment method (crack sealing or filling), a new overlay is generally placed in order to increase the life of the pavement and when linear crack appears it is again treated with crack sealing or filling. The use phase is not considered in this study as this phase will not have significant effect (similar environmental contribution for both treatment types) from the perspective of crack treatment methods.

Figure 7-1. Crack filling and sealing process (a) Selection of cracks; (b) Router; (c); Routed crack; (d) Crack cleaning; (e) Sealant material installation with squeegee; (f) complete installation of crack treatment

Methodology

<u>Field</u>

Functional unit

The functional units considered for this study are: (a) 1 km of asphalt pavement, (b) road width 13 m (traffic lanes 2 × 3.75 m + inner shoulder 1m), (c) crack density 0.45m/km, (e) an asphalt overlay of 80 mm is used for the maintenance strategy, (e) time scale 35 years, (f) 5000 vehicles/day.

Filling and sealing configuration selection

Abilene district test site database was used for the analysis of crack treatments configurations. For this study two types of cracks have been selected for the installation which are 3mm or approximately 1/8" in width. The first one is longitudinal cracks which develop longitudinally along the pavement centerline. Another one is transverse cracks which occur perpendicularly to the center line of the pavement. Cracks designated for crack sealing treatment were routed before putting the sealant material into the cracks. Routing incorporates the use of a router to open all the cracks up to a uniform width and depth. The average configuration profile for crack filling was considered 3.2 mm by 6.4 mm (1/8 inch x 1/4 inch) [W (mm/inch) x D (mm/inch)]. Routing was done on a 1x1 profile or 12.7 mm by 12.7 mm (1/2 inch by 1/2 inch). In order to observe the environmental impact with a small reservoir for crack sealing treatment, the study also considered to add a 9.5 mm by 9.5 mm (3/8 inch by 3/8 inch) configuration.

Estimated sealing length and amount of materials

Sealing length was considered 450 m per kilometer road (density of 0.45) for both treatment types. It was estimated that 11.635 kg, 100.425 kg and 55.11 kg polymer modified bitumen used for the treatment of crack filling (1/8 x 1/4), sealing (1/2 x 1/2) and sealing (3/8 x 3/8), respectively. The amount of materials was calculated in the following way:

Crack filling (1/8 x 1/4)

Cross sectional area of reservoir = (0.125 in x 0.25 in) = 0.03 in^2

Volume of reservoir (1 lin ft of crack) = 1ft x (0.03/144 ft^2) = 0.000208 ft^3

Gross application rate (no waste) = 73.31 (lb/ft^3) x 0.000208 = 0.0152 lb/lin ft of crack

Net application rate (15% waste) = 1.15 x 0.0152 = 0.01748 lb/lin ft of crack

Total material required = 0.01748 x 3.28084 x 450 x 0.454 = 11.635 kg/km

Crack sealing (3/8 x 3/8)

Cross sectional area of reservoir = (0.375 in x 0.375 in) = 0.140625 in^2

Volume of reservoir (1 lin ft of crack) = 1ft x (0.140625/144 ft^2) = 0.000977 ft^3

Gross application rate (no waste) = 73.31 x 0.000977 = 0.0716 lb/lin ft of crack

Net application rate (15% waste) = 1.15 x 0.0716 = 0.08234 lb/lin ft of crack

Total material required = 0.08234 x 3.28084 x 450 x 0.454 = 55.11 kg/km

Crack sealing (1/2 x 1/2)

Cross sectional area of reservoir = (0.5 in x 0.5 in) = 0.25 in^2

Volume of reservoir (1 lin ft of crack) = 1ft x (0.25/144 ft^2) = 0.00174 ft^3

Gross application rate (no waste) = 73.31 x 0.00174 = 0.13 lb/lin ft of crack

Net application rate (15% waste) = 1.15 x 0.13 = 0.15 lb/lin ft of crack

Total material required = 0.15 x 3.28084 x 450 x 0.454 = 100.425 kg/km

Equipment

Air compressor and hot melt equipment are used for both treatment types. High pressure air blasting is effective and efficient for removing dust, debris and some loosened AC fragments. Router was only used for the crack sealing treatment to cut the face of the crack. Air compressor and hot melt machine operates on diesel fuel and consumption was considered 0.141 liter/m^2. The diesel consumption for router was assumed to be half (0.071 liter/m^2). The amount of diesel consumption was calculated in the following way:

Crack filling (1/8 x 1/4) = 0.25 x 0.0254 x 450 x 0.282 = 0.806 liter/m^2

Crack sealing (3/8 x 3/8) = 0.375 x 0.0254 x 450 x 0.353 = 1.51 liter/m^2

Crack sealing (1/2 x 1/2) = 0.5 x 0.0254 x 450 x 0.353 = 2.015 liter/m^2

Estimated service period

A survey of crack sealing and filling procedures was developed and distributed in Texas in order to estimate the service period of crack treatment. The response was received and analyzed. Decker (2014) conducted a survey on 157 individual represents 28 state Department of Transportations (DOTs), 106 countries, 3 cities, 2 Federal Highway Administration (FHWA), 1 Canadian province, 2 U.S. contractors and 1 contractor from New Zealand. They were asked to estimate the typical life span for crack sealing and crack filling on both major and minor roads. They concluded that majority of the respondents think crack sealing on both major and minor roads can perform for 5-10 years, but that crack filling will only last 1-4 years. Yildirim et al. (2006) reported that crack sealing without routing configuration using hot-pour sealant materials have a typical life cycle of 3-5 years. Rajagopal (2011) reported that their prediction model indicated a life span of 3.6 years for crack filling treatment. According to the intensive literature review and survey from the Texas districts, the study considered that the pavement could stand with crack filling for 3 years and crack sealing for 5 years.

Life cycle assessment

Calculation of life cycle inventory (LCI)

In order to achieve the goal of the study, a life cycle inventory (LCI) that quantifies the energy, material extraction, sealant production, construction, and maintenance was developed. A wide range of published reports and databases were analyzed to quantify the energy and emission data for each process and activity defined as part of the system. Then the inventory data for each specific phase of crack treatment were collected from the peer reviewed journals. Inventory loadings of bitumen and polymer modified bitumen production were collected from a report published by European bitumen industry (Eurobitume, 2012). Emission of equipment during construction and maintenance input data were collected from another pilot study report (Stripple, 2001). The result of the inventory analysis is a summary of all inflows and outflows related to the "functional unit" (Huang et al. 2009). All inventory loadings for material phase were converted to ton to kilogram. The inventory loadings were characterized by the multiplication of corresponding unit characterizing factor of each emission category and Table 7-2 illustrates those impact categories along with their unit. The characterized loadings were multiplied with the respective treatment factor (amount of materials required for each treatment type) for estimating the impact assessment. The result of the each impact category is the total of all the individually characterized inventory loadings in each category. It has been shown in equation (1).

Impact assessment = Inventory loadings x Characterization factor x treatment factor……….(1)

Table 7-2. Classification and characterization of inventory loading (Huang et al., 2009)

Inventory loading	Life cycle phases	Impact category	Impact category area	Unit of characterization factor	Value of characterization factor
Aggregate, Bitumen		Depletion of minerals		ton minerals	1
Energy (GJ)		Depletion of fossil fuels		GJ	1
CO_2 CH_4 N_2O		Global warming		Kg CO_2-eq. (100 years)	1 23 296
SO_2 NO_2 NH_3		Acidification		Kg SO_2-eq.	1 0.7 1.88
SO_2 NO_2 CO CH_4 NMVOC		Photo oxidant formation		Kg C_2H_4-eq	0.048 0.028 0.027 0.006 1
SO_2 NO_2 CO HC NMVOC PM NH_3 Heavy Metals	Material Construction	Human toxicity	Emission to air	Kg 1,4-dichlorobenzene-eq.	0.096 1.2 2.4 5.7E + 05 0.64 0.82 0.1 5.1E + 05
HC As Cd Pb Hg	Maintenance	Human toxicity	Emission to fresh water	Kg 1,4-dichlorobenzene-eq	2.8E + 05 950.6 22.9 12.3 1426
NMVOC HC As Cd Pb Hg		Eco toxicity	Emission to air	Kg 1,4-dichlorobenzene-eq	3.2E-11 1480 7.8E + 04 3.7E + 05 2.4E + 03 4.1E + 05
HC As Cd Pb Hg		Eco toxicity	Emission to fresh water	Kg 1,4-dichlorobenzene-eq	1.1E + 04 4.0E + 04 7.4E + 04 3.7E + 02 7.2E + 04
NO_2 NH_3 COD PO_4 Nitrate P N		Eutrophication		Kg PO_4-eq	0.13 0.35 0.022 1 0.1 3.07 0.42

(IPCC: Intergovernmental Panel on Climate Change; WMO: World Meteorological Organisation; IISA: International Institute of Applied System Analysis; CML: Institute of Environmental Sciences, Leiden University; EMEP: Convention on Long-range Transboundary air pollution; SAFEL: Swiss Agency for the Environment, Forests and Landscape)

For example, all types of emissions (CO_2, CH_4, N_2O) that could contribute to global warming were grouped under the impact category "Global warming". Based on the findings from the literature review eight impact categories were selected for LCA. Table 7-3 presents the sample calculation for global warming potential.

Table 7-3. Calculation of global warming (Kg CO_2-eq.) for material phase

Inventory	Emission per kg (kg)	Characterization factor	Crack filling (11.635 kg)	Crack sealing	
				1/2 x 1/2 (100.425 kg)	3/8 x 3/8 (55.11 kg)
Bitumen production					
CO2	0.192	1	2.234	19.282	10.581
CH4	6.56 E-04	23	0.175	1.506	0.827
N2O	5.07 E-05	296	0.175	1.506	0.827
Total			2.584	22.294	12.235
PMB production					
CO2	0.326	1	3.793	32.739	17.966
CH4	1.20 E-03	23	0.326	2.812	1.543
N2O	5.41 E-05	296	0.186	1.607	0.882
Total			4.305	37.158	20.391
Total			6.889	59.452	32.626

Strategy

The quantification of long term environmental emission of crack sealing and filling was based upon two categories:

i) Initial emissions

ii) Emissions during 35 years of service period

As it is obvious that the initial emissions of crack sealing is more compared to crack filling due to the use of extra material and equipment. However, the service period is longer with crack sealing compared to crack filling. A 35 year analysis period was established to calculate the long term emissions in between these two treatment types. The study considered that a new asphalt overlay would be placed after the service period of each treatment type. For example, at the beginning a new asphalt mat has been placed. After two years linear cracks appeared on the surface of the pavement. For those linear cracks, crack filling and crack sealing treatment has been given. Crack filling and crack sealing treatment will last for 3 years and 5 years, respectively. With crack filling treatment a new asphalt mat will be again placed after 5 years and with crack sealing after 7 years. Figure 7-2 presents the strategy to calculate the long term emissions of both treatment types. This is one of the reasons behind the consideration of a 35 year analysis period to analyze the long term environmental burdens between these two treatment types. In between 35 years, resealing with crack filling treatment will be performed 7 times and with crack sealing 5 times. Apart from that, the new pavement technology such as perpetual pavement which can last more than 50 years can be an ideal pavement type for considering this routine maintenance of crack treatment. It is important that regardless of the analysis period selected, the analysis period should be the same for all alternatives.

	Crack Filling					Crack Sealing				
	New Asphalt Mat	Crack Filling	Totals	Running Total	Event Description	New Asphalt Mat	Crack Sealing	Totals	Running Total	Event Description
Years	emission/km	emission/km	219.88			emission/km	emission/km	165.18		
0	27.38		27.38	27.38	A new asphalt mat has been placed.	27.38		27.38	27.38	A new asphalt mat has been placed.
1			-	27.38				-	27.38	
2		0.12	0.12	27.50	A small crack appears and it is filled.		0.18	0.18	27.56	A small crack appears and it is sealed.
3			-	27.50				-	27.56	
4			-	27.50				-	27.56	
5	27.38		27.38	54.88	New overlay mat is placed.			-	27.56	
6			-	54.88				-	27.56	
7		0.12	0.12	55.00	A small crack appears and it is filled.	27.38		27.38	54.94	New overlay mat is placed.
8			-	55.00				-	54.94	
9			-	55.00			0.18	0.18	55.12	A small crack appears and it is sealed.
10	27.38		27.38	82.38	New overlay mat is placed.			-	55.12	
11			-	82.38				-	55.12	
12		0.12	0.12	82.50	A small crack appears and it is filled.			-	55.12	
13			-	82.50				-	55.12	
14			-	82.50		27.38		27.38	82.50	New overlay mat is placed.
15	27.38		27.38	109.88	New overlay mat is placed.			-	82.50	
16			-	109.88			0.18	0.18	82.68	A small crack appears and it is sealed.
17		0.12	0.12	110.00	A small crack appears and it is filled.			-	82.68	
18			-	110.00				-	82.68	
19			-	110.00				-	82.68	
20	27.38		27.38	137.38	New overlay mat is placed.			-	82.68	
21			-	137.38		27.38		27.38	110.06	New overlay mat is placed.
22		0.12	0.12	137.50	A small crack appears and it is filled.			-	110.06	
23			-	137.50			0.18	0.18	110.24	A small crack appears and it is sealed.
24			-	137.50				-	110.24	
25	27.38		27.38	164.88	New overlay mat is placed.			-	110.24	
26			-	164.88				-	110.24	
27		0.12	0.12	165.00	A small crack appears and it is filled.			-	110.24	
28			-	165.00		27.38		27.38	137.62	New overlay mat is placed.
29			-	165.00				-	137.62	
30	27.38		27.38	192.38	New overlay mat is placed.		0.18	0.18	137.80	A small crack appears and it is sealed.
31			-	192.38				-	137.80	
32		0.12	0.12	192.50	A small crack appears and it is filled.			-	137.80	
33			-	192.50				-	137.80	
34			-	192.50				-	137.80	
35	27.38		27.38	219.88	New overlay mat is placed.	27.38		27.38	165.18	New overlay mat is placed.

Figure 7-2. Long term emissions calculation sample of crack filling and sealing treatment

Results

Based on the calculations, summary tables for each life cycle phase of crack treatment method have been provided in this section. Tables 7-4 and 7-5 present the environmental burdens of three configurations (crack filling and crack sealing) of crack treatment in material and construction phase. The material phase of crack treatment method has more environmental emissions compared to the construction phase regardless of the impact categories. Among the three treatment types crack sealing with (1/2 x 1/2) configuration is found to have high impacts to the environment. Table 7-6 shows the result of environmental emissions of maintenance phase due to overlay. All of these life cycle phases of crack treatment were evaluated on eight impact categories.

Material phase

Table 7-4. Impact results from life cycle inventory for crack treatment methods

Impact category	Unit	Crack filling (per km)	Crack sealing (3/8 x 3/8) (per km)	Crack sealing (1/2 x 1/2) (per km)
Depletion of minerals	kg minerals	11.635	100.425	55.11
Depletion of fossil fuel	GJ	0.133	1.151	0.632
Global warming	Kg CO2-eq. (100 years)	6.889	59.452	32.626
Acidification	Kg SO2-eq.	0.050	0.432	0.237
Photo oxidant formation	Kg C2H4-eq	0.011	0.098	0.053
Human toxicity (air)	Kg 1,4-dichlorobenzene-eq.	1241.064	10341.19	5749.131
Human toxicity (water)	Kg 1,4-dichlorobenzene-eq.	814.45	7029.751	3857.701
Eco toxicity (air)	Kg 1,4-dichlorobenzene-eq.	3.597	30.784	17.043
Eco toxicity (water)	Kg 1,4-dichlorobenzene-eq.	32.002	276.218	151.579
Eutrophication	Kg PO4-eq	6.29E-03	0.055	0.030

Construction phase

Table 7-5. Impact results from life cycle inventory for crack treatment methods

Impact category	Unit	Crack filling (per km)	Crack sealing (3/8 x 3/8) (per km)	Crack sealing (1/2 x 1/2) (per km)
Depletion of minerals	kg minerals	-	-	-
Depletion of fossil fuel	GJ	0.0311	0.078	0.058
Global warming	Kg CO2-eq. (100 years)	2.249	5.622	4.213
Acidification	Kg SO2-eq.	0.016	0.039	0.029
Photo oxidant formation	Kg C2H4-eq	6.83E-04	1.71E-03	1.28E-03
Human toxicity (air)	Kg 1,4-dichlorobenzene-eq.	826.986	2067.464	1549.316
Human toxicity (water)	Kg 1,4-dichlorobenzene-eq.	406.224	1015.56	761.04
Eco toxicity (air)	Kg 1,4-dichlorobenzene-eq.	2.147	5.368	4.023
Eco toxicity (water)	Kg 1,4-dichlorobenzene-eq.	15.959	39.897	29.898
Eutrophication	Kg PO4-eq	2.63E-03	6.58E-03	4.93E-03

Maintenance phase

Table 7-6. Impact results from life cycle inventory for maintenance phase (placement of new asphalt overlay)

Impact category	Impact category area	Unit of characterization factor	Total (per km)
Depletion of minerals	Bitumen	kg minerals	7.8E+04
	Rock		1.16E+09
Depletion of fossil fuels		GJ	1957.316
Global warming		Kg CO2-eq. (100 years)	121482.73
Acidification		Kg SO2-eq.	589.585
Photo oxidant formation		Kg C2H4-eq	26.973
Human toxicity	Emission to air	Kg 1,4-dichlorobenzene-eq.	25161604.86
	Emission to fresh water	Kg 1,4-dichlorobenzene-eq.	12360040
Eco toxicity	Emission to air	Kg 1,4-dichlorobenzene-eq.	65331.64
	Emission to fresh water	Kg 1,4-dichlorobenzene-eq.	485573
Eutrophication		Kg PO4-eq	91.456

Initial impact of crack treatment techniques to the environment

Table 7-7 illustrates the results of initial impact of crack filling and sealing treatment which is a summation of material and construction phase. It can be observed that crack filling has less emissions during material and construction phase compared to sealing treatment.

Table 7-7. Initial impact of crack filling and sealing treatment to the environment

Impact category	Unit	Crack filling	Crack sealing (3/8 x 3/8)	Crack sealing (1/2 x 1/2)
Depletion of minerals	kg minerals	11.635	55.11	100.425
Depletion of fossil fuel	GJ	0.164	0.69	1.229
Global warming	Kg CO2-eq. (100 years)	9.138	36.839	65.074
Acidification	Kg SO2-eq.	0.066	0.266	0.471
Photo oxidant formation	Kg C2H4-eq	0.012	0.054	0.099
Human toxicity (air)	Kg 1,4-dichlorobenzene-eq.	2068.05	7298.447	12408.654
Human toxicity (water)	Kg 1,4-dichlorobenzene-eq.	1220.674	4618.741	8045.311
Eco toxicity (air)	Kg 1,4-dichlorobenzene-eq.	5.744	21.066	36.152
Eco toxicity (water)	Kg 1,4-dichlorobenzene-eq.	47.961	181.477	316.115
Eutrophication	Kg PO4-eq	8.92E-03	0.035	0.062

Impacts during 35 years of analysis period

Table 7-8 shows the long term environmental impact of crack filling and sealing treatment after 35 years of analysis period. It is evident from the table that crack sealing treatment has more environmental burdens in a long run. The reason is due to the less routine maintenance with crack sealing treatment.

Table 7-8. Long term impact of crack filling and sealing treatments

Impact category	Unit	Crack filling	Crack sealing (3/8 x 3/8)	Crack sealing (1/2 x 1/2)
Depletion of minerals	kg minerals	624081.45	468275.55	468502.13
Depletion of fossil fuel	GJ	15659.68	11747.35	11750.04
Global warming	Kg CO2-eq. (100 years)	971925.81	729080.58	729221.75
Acidification	Kg SO2-eq.	4717.14	3538.84	3539.86
Photo oxidant formation	Kg C2H4-eq	215.87	162.11	162.33
Human toxicity (air)	Kg 1,4-dichlorobenzene-eq.	201307315.23	151006121.40	151031672.43
Human toxicity (water)	Kg 1,4-dichlorobenzene-eq.	98888864.72	74183333.71	74200466.56
Eco toxicity (air)	Kg 1,4-dichlorobenzene-eq.	522693.54	392095.17	392170.60
Eco toxicity (water)	Kg 1,4-dichlorobenzene-eq.	3884919.73	2914345.39	2915018.58
Eutrophication	Kg PO4-eq	731.71	548.91	549.05

Discussions/Interpretation

Initial and long term emissions of crack treatment techniques

Figure 7-3 shows the percentage environmental burdens of each treatment type to the environment during material and construction phase. It is evident from the figure that the initial emissions of two configurations of crack sealing are very high compared to filling technique. Table 7-9 presents initial percentage increase and long term percentage reduction of environmental emissions with crack sealing compared to crack filling treatment.

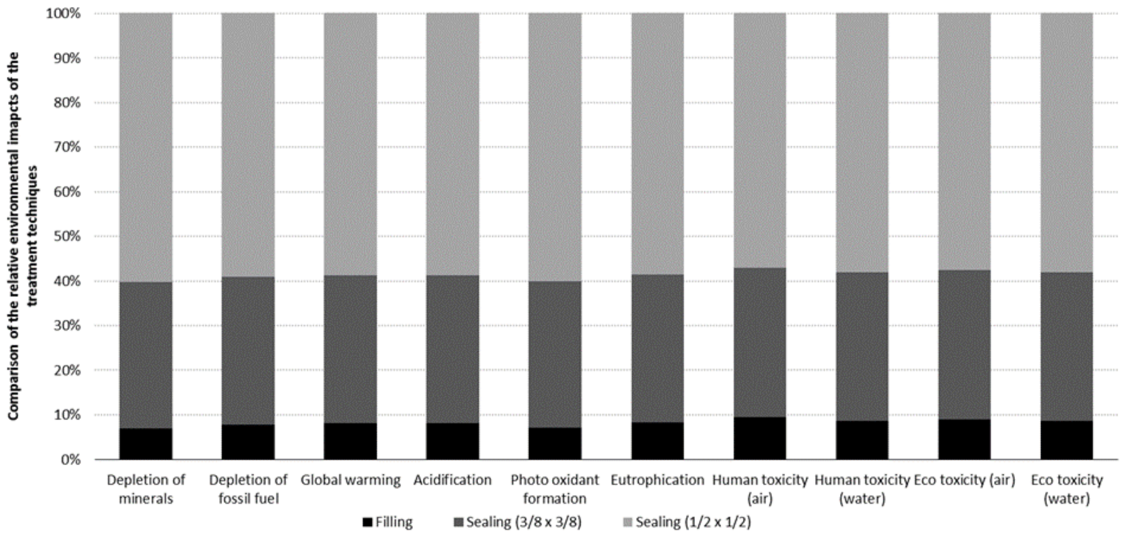


Figure 7-3. Initial emissions of crack filling and sealing treatment to the environment

Table 7-9. Initial percentage increase and long term percentage reduction of environmental emissions with crack sealing compared to crack filling treatment

Impact category	Initial percentage increase (%)		Long term percentage reduction (%)	
	Crack sealing (3/8 x 3/8)	Crack sealing (1/2 x 1/2)	Crack sealing (3/8 x 3/8)	Crack sealing (1/2 x 1/2)
Depletion of minerals	373.66	763.13	24.97	24.93
Depletion of fossil fuel	320.73	649.00	24.98	24.97
Global warming	303.14	612.13	24.99	24.97
Acidification	303.14	613.64	24.98	24.96
Photo oxidant formation	350.00	725.00	24.90	24.80
Human toxicity (air)	252.91	500.02	24.99	24.97
Human toxicity (water)	278.38	559.09	24.98	24.97
Eco toxicity (air)	266.75	529.39	24.99	24.97
Eco toxicity (water)	278.38	559.11	24.98	24.97
Eutrophication	292.38	595.07	24.98	24.96

Depletion of materials and photo oxidant formation are observed to have the highest percentage increase among all the eight categories. On the other hand, human toxicity (air) is found to have the lowest percentage increase due to the difference in treatment type. Global warming and acidification impact seemed to have same percentage increase. Also, human toxicity and eco toxicity are found to have similar percentage increase in terms of water. The configuration parameter of crack sealing treatment seems to play an important role where approximately double percentage increase at initial environmental emissions is calculated with 1/2 x 1/2 compared to 3/8 x 3/8 routing configuration.

Figure 7-4 presents the long term emissions of each treatment type to the environment after 35 years of analysis period. The opposite trend is observed with initial environmental emissions where crack filling has the less significant impact to the environment compared to sealing technique. It is worth to note that the calculation of long term emissions includes the maintenance phase. As a result, the low long term emissions can be obtained with the treatment which does not need to perform frequently. As mentioned earlier in a 35 year preservation period, crack filling needs to perform 7 times whereas with sealing only 5 times. The savings of two asphalt overlay treatment to the pavement with sealing technique compensate its initial high amount of environmental emissions.

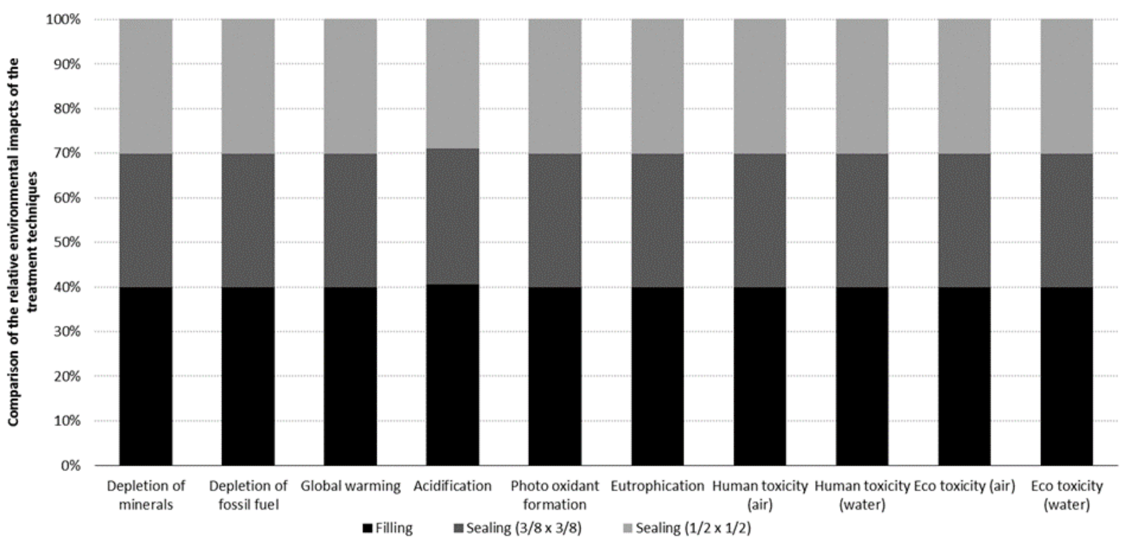


Figure 7-4. Long term emissions of crack filling and sealing treatment to the environment

Table 7-9 presents the percentage reduction of environmental emissions with crack sealing compared to filling treatment over a 35 year analysis period. Approximately 25%

reduction in environmetal emissions can be achieved with sealing technique compared to filling after 35 years of analysis period. Also, the configuration parameter of sealing treatment does not seem to play an imporatnt role to reduce the long term emissions. The reason is that the environmental burdens of maintenance phase is very high compared to the individual sealing configuration and in a long run the difference in configuration is less significant to the overall contribution.

Summary and Conclusions

The goal of the study is to evaluate the initial and long term environmental burdens of crack filling and sealing treatment in asphalt pavement. To accomplish the objective, a comprehensive inventory database was developed and characterized the inventory loading using LCA model in order to get impact to the environment. The initial and long term environmental emissions were calculated in three life cycle phases (material, construction and maintenance) and quantified on eight impact categories. Based on the results of the study, following conclusions can be drawn:

1) The initial environmental emissions of crack sealing is very high compared to filling treatment due to the use of extra material and equipment in the material and construction phase, respectively.

2) Initial environmental impact of depletion of materials and photo oxidant formation was found to have the highest percentage increase whereas human toxicity (air) is observed to have the lowest percentage increase among all the eight impact categories.

3) The environmental emissions can be reduced by approximately 25% with crack sealing compared to filling treatment over a 35 years of service period meaning that a

successful crack sealing implementation can ensure less emissions compared to crack filling treatment.

4) The configurations parameter of crack sealing treatment seemed to have a significant effect during the initial environmental emissions. However, in a long run this parameter is found to be insignificant.

5) The methodology used for this study (development of inventory loading and using LCA model) has the potential to be implemented for the future study in order to get the environmental emissions on different pavement maintenance methods.

This chapter (VII) includes a part of the following publications;

Mazumder, M., Sriraman, V., Kim, H. H., Lee, S.-J., "Quantifying the Environmental Impacts of Crack Filling and Sealing Treatment in Hot Mix Asphalt Pavement" *Innovative Infrastructure Solutions*, 3: 61. https://doi.org/10.1007/s41062-018-0161-4 (July 2018).

CHAPTER VIII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

Crack sealant materials are inserted into pavement cracks in order to reduce the intrusion of water and contaminants through cracks into underlaying layers. Sealing these cracks early with potential crack sealant material can ensure pavement longevity and delay pavement deterioration. The implementation techniques of crack sealant material also play a vital role to its performance. Crack filling and sealing are the two techniques used to insert the sealant material into the cracks. The implementation of best crack treatment techniques along with a new prospective crack sealant material can increase the service life of pavement. This study was initiated to characterize a new prospective crack sealant material and find out the most effective crack treatment techniques in terms of field performance, cost effectiveness, and environmental impact.

Five different amounts (0, 5, 10, 15 and 20%) of SIS modifier were used to produce the SIS binder. The physical, rheology and microstructural properties were studied using rotational viscosity (RV), dynamic shear rheometer (DSR), bending beam rheometer (BBR), atomic force microscope (AFM), and environmental scanning electron microscope (ESEM). In addition, the absorption and reflection properties of the SIS modified binder were evaluated and prospective of SIS modifier as a crack sealant material are discussed in Chapter IV.

The field performance between two implementation techniques (crack filling and crack sealing) of crack sealant material evaluated and the results are reported in Chapter V. For that purpose, four test sites in Texas have been selected presenting different climatic regions and Annual Average Daily Traffic (AADT) in Texas: Fort Worth, Corpus Christi, Abilene, and Brownwood.

HDM-III modelling and field cost input were conducted and analyzed in order to find out the best cost effectiveness practice between crack filling and sealing treatment. These two crack treatment methods are used as two maintenance strategies in HDM-III and economic analysis between these two strategies were performed in terms of agency cost, capital cost and net present value over a 25 year analysis period based upon ADT, altitude and road length. Also, simulations have been performed to select the cost effective strategy with the increase of unit cost due to routing. On the other hand, for field validation potential cost factors were identified, recorded and analyzed for both treatments to find out the initial, average annual and life cycle cost upon the data obtained from the four test sites in Texas. The results are reported in chapter VI.

The quantification of environmental impact of crack sealing and filling techniques are documented in Chapter VII. The environmental burdens are quantified and compared between these two treatment types during the construction and over a 35 year analysis period on three life cycle phases (material, construction and maintenance). The emissions to the environment corresponding to each life cycle phase for these two treatment techniques were quantified on eight impact categories.

Conclusions

Based on the results of this research, the following conclusions were made:

- SIS modifier a potential to become a crack sealant material (blending with asphalt material) based on the physical, rheology and microscopy properties. It has significant effect on the viscosity, rheology and cracking performance of the binder. The microstructure properties exhibited a new oval phase which has a significant contribution to the cracking properties of the binder.
- The survey on crack treatment techniques in Texas Districts showed that most of them do not use the crack sealing treatment due to three reasons which are: i) insufficient knowledge about benefits, ii) costly and uncommon practice, and iii) lack of proper guidelines.
- After final monitoring, treatment effectiveness of 50.3%, 44.8%, 31% and 23.4% more was obtained in Fort Worth, Corpus Christi, Brownwood and Abilene, respectively, with sealing compared to filling treatment. On an average, treatment effectiveness of sealing technique was declined by 19% whereas 43% reduction was observed for filling technique due to winter weather.
- HDM-III modelling showed that crack sealing is a more cost effective pavement maintenance compared to crack filling over a long period of time. Agency and capital costs can be reduced significantly by implementing crack sealing treatment. Net present value of crack sealing is higher compared to crack filling based on a 25-year analysis period.
- Along with the modelling, a cost analysis was also performed using the cost data collected from the test sites. The analysis indicated that on average, an approximate

45% initial cost increase was estimated using the two routing methods of crack sealing. Annual average and life cycle costs were shown that crack sealing is a more cost effective pavement maintenance compared to crack filling over a long period of time. Agency cost was observed to be reduced by approximately 24% with a crack sealing treatment based on 35-year analysis period.

- Based on the analysis of environmental impacts between crack sealing and filling treatment, it is evident that the initial environmental emissions of crack sealing treatment is higher compared to filling technique. However, this environmental burdens can be compensated along with an approximately 25% reduction in emissions by implementing crack sealing treatment over a long period.

Recommendations for Future Research

On the completion of this study, the following topics of future research are recommended:

- In-depth investigation to find out correlation between new oval phase and stiffness of SIS binder through chemical characterization.
- Actual long term performance and service life of crack sealing treatment over a long period of time until it fails.
- Field performance of SIS modified crack sealant material implemented with crack sealing technique.

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