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Crack Sealing and Filling: Best Practices

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16. Abstract

This study investigated the current state of practice for crack sealing/filling. In addition, the INDOT crack sealing/filling practice was experimentally evaluated for the effectiveness of crack sealing/filling, the effectiveness of routing, the performance of the different types of crack sealants and fillers, the validity of sealant performance grade system, and the crack sealing/filling equipment performance. The key findings from an extensive literature review and nationwide/statewide survey performed in 2012 are the following: 1) 65% of the responses indicated that the routing is required for the crack sealing/filling application; 2) ASTM D 6690 Type II was the most widely used sealant type and only Missouri and Indiana included emulsions in their specifications as crack sealing/filling materials; and 3) crack sealing/filling equipment availability and their maintenance were the biggest concerns.

Based on the two-year experimental investigation, the crack sealing/filling was determined to be effective in preventing the occurrence of pavement surface crack distress. The crack sealing/filling was concluded to be effective in maintaining crack integrity and resisting sealant and filler deformations due to the seasonal crack movement. The routing was not determined to be effective in terms of the pavement performances. However, Adhesive/Cohesive/Spalling (ACS) failure results showed that the routed sections significantly outperformed the non-routed sections. In addition, the test results indicated that the ASTM 6690 Type II crack sealants performed relatively well in terms of pavement and crack performance. The correlation between the sealant performance grades and the pavement and crack performances with different types of sealants and fillers were poor and insignificant.

The mixed results regarding the effectiveness of the routing were obtained from the literature review and the field evaluation. As a result, it was recommended from the SAC meeting that routing in the 2090 Activity be limited to a single transverse crack (reflective cracks) on asphalt concrete over concrete pavements. INDOT currently uses the ASTM Type II crack sealants, which showed an overall good pavement and crack performances in the evaluation. Therefore, the current INDOT crack sealant material selection process (ASTM Type II) is concluded to be adequate.

The experimental results showed that the cracks on wet pavement treated with HAL had significantly higher bonding between the materials and asphalt pavement surface than the cracks treated with the conventional air compressor. Therefore, the incorporation of a hot air lance in the wet condition is recommended to extend the operable time and seasonal availability for crack filling and sealing construction (2070 and 2090 Activities).

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EXECUTIVE SUMMARY

CRACK SEALING AND FILLING: BEST PRACTICES

INTRODUCTION

The Indiana Department of Transportation (INDOT) performs in-house crack sealing/filling practices on pavements based on INDOT Performance Standard Activity 2070 for Crack Filling and Activity 2090 for Crack Route and Seal. Those activities are the primary pavement preservation techniques considered in the INDOT Pavement Preservation Initiative (PPI).

Even though crack sealing/filling has been used popularly on pavements, there are mixed research findings regarding the effectiveness of sealing/filling and routing. For instance, a study for the Ohio Department of Transportation (ODOT) concluded that the crack sealed pavements exhibited better performance in terms of pavement condition rating than the untreated section on a 5-year life cycle. Another study conducted with Long-Term Pavement Performance (LTPP) data in 2012 on short-term effectiveness of pavement treatment on International Roughness Index (IRI) reported that crack sealing application offered a significant jump in pavement performance in terms of IRI down to 28 in./mile. However, two Indiana studies (Fang et al., 2003; Ong et al., 2010) found that there were no significant IRI differences between sealed and untreated pavements. For the effectiveness of routing in crack sealing practice, Masson (1997) found that routing on an asphalt concrete pavement created micro-cracks at the bitumen aggregate interface and within aggregates. A recent Illinois study concluded that routing is not recommended for all types of cracks, just for working cracks. The controversial effectiveness in terms of sealing/filling and pavement performances should be clarified for INDOT's crack sealing/filling practice. There is also a need for a study to evaluate INDOT's crack sealing/filling and routing effectiveness.

INDOT currently uses AE-90S for the crack filling application (2070 Activity) and hot poured sealants (crumb rubber asphalts) for the crack sealing application (2090 Activity). Various materials are available in the crack sealing/filling industry. Specifically, this study found that more than 70 products were listed in the approved/qualified product lists of 17 state DOTs. Accordingly, having a proper material selection guide is important for ensuring crack sealing/filling performance. INDOT uses American Society for Testing and Materials (ASTM) D 6690 Type II sealant. Recently, "Performance Based Sealant Grading (SG)" was introduced with better correlations between sealant rheological properties and field performances at low temperature. Therefore, there is a need to evaluate SG to assess its validity and applicability to INDOT.

INDOT Specification Section 408 specified that crack sealing/filling operations cannot be performed when either a pavement surface is not dry or the ambient temperature is below 40°F. INDOT conducts crack sealing/filling throughout the year and those conditions often pose limits on the available season and operation time. A hot air lance (HAL) is an option to increase the construction time and help the production rates. HAL produces high velocity hot air, directed towards the pavement surface, thus removing dust and moisture from the crack.

A Strategic Highway Research Program (SHRP) manual of practice recommends a HAL for removal of dust and moisture. HAL is popular in other DOTs. For instance, a HAL application is a common practice for crack sealing in Illinois. INDOT has very limited experience with HAL: only 3 out of 29 INDOT Sub-districts have any experience with a HAL. Consequently, the performance and applicability of the HAL need to be reviewed for its possible vitalization in Indiana.

INDOT requires cracks to be routed prior to the placement of sealant. A few issues with routers have been reported, such as safety, production rates, and their maintenance. A new router, called the RapidRouter™ (RR), was recently introduced to INDOT. RR is a skid steer mounted router controlled by a skid loader controller. Thus, an operator can be in a safer environment with constant production rates and less operator fatigue. This study evaluates the performance of a prototype RR available to INDOT.

The primary objectives of the proposed research project are: (1) to review the current state of practice for crack sealing/filling; (2) to evaluate the effectiveness of crack sealing/filling; (3) to assess the effectiveness of routing cracks; (4) to evaluate the performance of crack sealing/filling materials; (5) to review the performance-based sealant grading system; and (6) to evaluate the crack sealing/filling equipment performance.

FINDINGS

An extensive literature review and nationwide/statewide survey in 2012 were performed to understand the state of crack sealing/filling practices. The key findings are as follows: (1) most state agencies used both sealing and filling terminologies interchangeably; (2) 65% of the responses indicated that routing is required for crack sealing/filling application; (3) ASTM D 6690 Type II was the most widely used material type with only Missouri and Indiana including emulsions in their specifications as crack sealing/filling materials; (4) over 70 products were listed in the approved/qualified product lists of 17 state DOTs; (5) most of the sealants and fillers are produced by Crafco, Deery, McAsphalt, and Right Pointe; (6) INDOT performed crack sealing throughout the year while crack filling was primarily conducted during the winter season; (7) most INDOT Sub-districts shared crack sealing equipment within their respective Districts. Crack sealing/filling equipment availability and their maintenance were the biggest concerns.

The experimental evaluation was performed to assess the effectiveness of crack sealing/filling applications, routing, material performance, and equipment performance. Five crack sealant and four crack filling materials were tested utilizing IRI, Falling Weight Deflectometer (FWD), surface crack evaluation, adhesive/cohesive/spalling (ACS) failure, Ultrasonic Pulse Velocity (UPV), texture scanner, and flow rate. In addition, the new sealant grading system was conducted with the same nine crack sealing/filling materials and the performance of the RR and HAL were evaluated. The following conclusions were drawn based on the laboratory tests and field experimental evaluations.

Effectiveness of Crack Sealing/Filling

- *Pavement performance:* The IRI and pavement surface crack evaluation showed that the crack sealing/filling sections performed slightly better than the do-nothing section. The Load Transfer Efficiency (LTE) and asphalt modulus results showed that the crack sealing/filling sections did not outperform the do-nothing section. Thus, the crack sealing/filling was determined to be effective in preventing pavement surface crack distress occurrence.
- *Crack performance:* UPV on crack and the texture scanner results indicated that the crack sealing/filling sections outperformed the do-nothing section. Thus, the crack sealing/filling was concluded to be effective in maintaining crack integrity and resisting sealant and filler deformations due to seasonal crack movement.

Effectiveness of Routing

- *Pavement performance:* The test results from IRI, LTE, asphalt modulus, and pavement surface crack showed that the routed sections did not outperform the non-routed sections. Therefore, the routing was not determined to be effective in terms of the pavement performances.
- *Crack performance:* UPV and the texture scanner results indicated that the routed sections did not outperform the non-routed sections. However, ACS failure results showed that the routed sections significantly outperformed the non-routed sections.

Material Performance

- In terms of ACS failure PG 64-22 binder and RoadSavor 222 showed the best performances for crack filling and sealing applications, respectively. The test results indicated that the ASTM 6690 (2007) Type II crack sealants performed relatively well in terms of pavement and crack performances.
- The correlations between the ACS failure and the other tests were overall very poor, which indicates that material performances (ACS failures) do not significantly influence pavement and crack performance within a two-year period.

Sealant Grade

- The correlation between the sealant performance grades and the pavement and crack performances with different types of sealants and fillers were poor and insignificant.

Equipment Performance Evaluation

- *RapidRouter™ (RR):* RR and the manual router had similar production rates (20 to 40 sec/transverse crack) in about half-mile sections. RR can be a safer option.
- *Hot Air Lance (HAL):* The cracks treated with HAL had significantly higher bonding between the materials and the asphalt pavement surfaces than the cracks treated with the conventional air compressor on a wet surface. However, there was no significant difference in bonding strength between them on a dry surface.

IMPLEMENTATION

Routing Practice

The mixed results regarding the effectiveness of the routing were obtained from the literature review and the field evaluation. Some literature and a recent study conducted by the Illinois DOT reported that routing is effective, and the Illinois study also concluded that routing was effective in minimizing ACS failures. However, routing was not determined to be effective in terms of ride quality, structural integrity, pavement surface crack, crack integrity, and material deformation for two years in the test sections. As a result, the Study Advisory Committee recommended that routing in the 2090 Activity be limited to a single transverse crack (reflective crack) on asphalt concrete over concrete pavements.

AE-90S Replacement

The test section results show that there are some better performing sealants and fillers than AE-90S. AE-90S costs about 65% of the average hot poured sealant and filler cost ($0.45) used in this study. However, considering the residue of AE-90S (e.g., 65%), the hot poured sealants have competitive pricing. Therefore, replacing AE-90S with the other crack sealants or fillers for the filling application (2070 Activity) should be considered.

Material Selection

INDOT currently uses ASTM Type II crack sealants, which from the evaluation showed overall good pavement and crack performances. The correlation between sealant performance grades of each material and the pavement and crack performance test results were poor and insignificant. Thus, the current INDOT crack sealant material selection process (ASTM Type II) is concluded to be adequate.

Hot Air Lance

The hot air lance (HAL) effectively cleans and dries the wet cracks and provides better bonding between the materials and the asphalt pavement surface than conventional air compressors. The incorporation of a HAL in wet conditions is recommended to extend operable time and the seasonal availability for crack filling and sealing construction (2070 and 2090 Activities).

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1. INTRODUCTION

1.1 Research Background

Crack sealing/filling is one of the most common pavement preservation options. Crack sealing/ filling, if applied correctly, is believed to reduce pavement deterioration by minimizing the infiltration of foreign objects (e.g., moisture and incompressible materials) into a pavement structure; thus extending the pavement life. Additional benefits may also include: (1) unit cost of crack sealing/filling is less than 6% of patching unit cost and (2) a general method of installation is very simple and which involves cleaning the crack using compressed air followed by the application of material (Masson, 1997). According to the manual of practice from the Strategic Highway Research Program (SHRP), crack sealing is the placement of materials into working cracks mostly after routing, and crack filling is the placement of materials into non-working cracks. Working cracks are defined as cracks with annual horizontal movement of 0.1 in. or more (Smith & Romine, 1999). For the purpose of this study, crack sealing will refer to crack repair with routing, and crack filling will refer to crack repair without routing.

Indiana Department of Transportation (INDOT) performs in-house crack sealing/filling practices on pavements based on guidelines in the INDOT Work Performance Standard specifying them as INDOT Performance Standard Activity 2070 for Crack Filling and Activity 2090 for Crack Route and Seal. Those activities are the primary pavement preservation techniques considered in the INDOT Pavement Preservation Initiative (PPI). In the 2010 Fiscal Year, INDOT treated 5,284 lane miles and 666 lane miles with crack filling and crack sealing, respectively. The other INDOT PPI treatments (e.g., seal coat, micro-surfacing, Ultra Thin Bonded Wearing Course, and 4.75 mm HMA) covered 915 lane miles.

Even though crack sealing/filling has been used widely on pavements, there are mixed research findings regarding the effectiveness of sealing/filling and routing. For instance, the Ohio Department of Transportation (ODOT) conducted study regarding the effectiveness of crack sealing on pavement serviceability and life. The study concluded that the crack sealed pavements exhibited better performance in terms of pavement condition rating than the untreated section on a 5-year life cycle basis (Rajagopal, 2011). Another study conducted with Long-Term Pavement Performance (LTPP) data in 2012 on the short-term effectiveness of pavement treatment on the International Roughness Index (IRI) reported that crack sealing application offered a significant jump in pavement performance in terms of IRI down to 28 in./mile (Lu & Tolliver, 2012). However, two Indiana studies found that there were no significant IRI differences between sealed and non-sealed pavements (Fang, Galal, Ward, & Haddock, 2003) and prior to and after the sealing application (Ong, Nantung, & Sinha, 2010). For the effectiveness of routing in crack sealing practice, Masson (1997) found that routing on an asphalt concrete pavement created micro-cracks at the bitumen aggregate interface and within aggregates. A recent Illinois study (Al-Qadi, Ozer, Yousefi, & McGhee, 2015) concluded that routing is not recommended for all types of cracks except working cracks. The controversial effectiveness in terms of sealing/filling and pavement performances should be reevaluated with an in-depth project-level investigation for the INDOT crack sealing/filling practice. There is also a need to evaluate the INDOT crack sealing/filling and routing effectiveness.

INDOT currently uses AE-90S for the crack filling application (2070 Activity) and hot poured sealant (crumb rubber asphalt) for the crack sealing application (2090 Activity). Various materials are available in crack sealing/filling industry. Specifically, this study found that more than 70 products were listed in the approved/qualified product lists of 17 state DOTs. Accordingly, having a proper material selection guide is important for ensuring crack sealing/filling performance. INDOT uses American Society for Testing and Materials (ASTM) D 6690 Type II sealant. Recently, "Performance Based Sealant Grading (SG)" was introduced with better correlations between sealant rheology properties and field performances at low temperature. Therefore, there is a need to evaluate SG to assess its validity and applicability to INDOT.

INDOT Specification Section 408 specified that crack sealing/filling operations cannot be performed when either a pavement surface is not dry or the ambient temperature is below 40°F. INDOT conducts crack sealing/filling throughout the year and those conditions often pose limits on the available season and operation time. Hot air lance (HAL) is a possible option to increase the construction time and help its production rates. HAL produces high velocity hot air, directed towards the pavement surface, thus removes dust and moisture from the crack. A Strategic Highway Research Program (SHRP) manual of practice recommends HAL for removal of dust and moisture (Smith & Romine, 1999). A HAL application is popular in other state agencies. Additionally, HAL is a common practice for crack sealing in Illinois. INDOT has very limited experience with HAL: only three out of 29 INDOT Sub-districts have experienced HAL. Consequently, the performance and applicability of the HAL needs to be reviewed for its possible vitalization in Indiana.

INDOT requires cracks to be routed prior to the placement of sealant. A few issues with routers have been reported, such as safety, production rates, and maintenance. A new type of router, called the RapidRouter™, was recently introduced to INDOT. RapidRouter™ is a skid steer mounted router that is controlled by a skid loader controller. Thus, an operator can be in a safer environment with constant production rates and less operator fatigue. This study evaluates the performance of a prototype Rapid Router™ available to INDOT.

1.2 Research Objectives

The primary objectives of the proposed research project are:

- to review the current state of practice for crack sealing/filling;
- to evaluate the effectiveness of crack sealing/filling;
- to assess the effectiveness of routing cracks;
- to evaluate the performance of the different types of crack sealants and fillers;
- to review the performance-based sealant grading system; and
- to evaluate the crack sealing/filling equipment performance.

1.3 Report Organization

This report is composed of six chapters. Chapter 1 presents the research background and objectives. Chapter 2 summarizes the literature review of state practices of 49 states, including Indiana, on crack sealing/filling as well as available evaluation methods for the performance of crack sealing/filling. Chapter 3 presents the results of the survey conducted on a nationwide and statewide levels regarding the general practices of crack sealing/filling. Chapter 4 discusses the experimental study conducted for the evaluation of crack sealing/filling performance in terms of sealing/filling, routing effectiveness and material performance along with performance-based sealant grading evaluation. Chapter 5 describes the field performance evaluation of crack sealing/filling equipment, such as the hot air lance (HAL) and RapidRouter™ (RR). The conclusions from this research and recommendations are given in chapter 6.

2. LITERATURE REVIEW

2.1 Terminology

Crack repair consists of crack sealing and crack filling. In general, crack sealing refers to placing material in the routed channel. Crack filling, on the other hand, refers to the placement of material on a non-routed crack. Consequently, materials used for crack sealing/filling are generally denoted as crack sealant and crack filler. According to the manual of practice from Strategic Highway Research Program (SHRP), definitions of crack sealing/filling are the following (Smith & Romine, 1999):

- *Crack Sealing:* The placement of specialized treatment materials above or into working cracks using unique configurations to prevent the intrusion of water and incompressibles into the crack.
- *Crack Filling:* The placement of ordinary treatment materials into non-working cracks to substantially reduce infiltration of water and to reinforce the adjacent pavement.

For the purpose of this study, crack sealing, crack filling, sealant, and filler will be used throughout the report.

2.2 INDOT Current Practice

2.2.1 INDOT Standard Specification Section 408

The project began in 2012, and the 2012 INDOT Standard Specification Section 408 was used to employ different terminologies than the terminologies used in the manual of practice from SHRP for crack sealing/filling activities, such as "routing and filling" and "sealing" cracks (INDOT, 2012). The 2016 INDOT Standard Specification has adopted the terminologies "Crack Sealing" and" Crack Filling" as defined by the manual of practice from SHRP. Regarding materials for crack filling (2090 Activity), AE-90 and AE-150 have been removed (INDOT, 2016). Table 2.1 summarizes all the changes made to 2016 INDOT Standard Specifications Section 408.

2.2.2 INDOT Work Performance Standard

INDOT Work Performance Standards provides detailed information for all pavement maintenance activities performed by INDOT including, but not limited to planning, crew size, equipment needed, work method, and special considerations. Each activity is assigned a code (i.e., four digit number) and the codes for crack sealing and filling activities are 2070 and 2090, respectively. Thus, crack sealing and filling activities are commonly denoted by their codes.

The work Performance Standard is based on the 2016 INDOT Standard Specification, and can serve as a field manual for INDOT employees on how each activity should be performed. However, a few minor differences have been observed and the details are the following:

- INDOT Specification specified the crack sealing or filling operations not to be performed when the ambient temperature is below 40°F. Work Performance Standard 2070 specified the activity not to be performed when temperature is below freezing.
- INDOT Specification specified air compressors to be capable of producing a minimum air pressure of 100 psi. Work Performance Standard required air compressor to be capable of producing a minimum air pressure of 110 psi.
- INDOT Specification specified cracks and joints, ½ in. or less in width, to be treated. Work Performance Standard, however, stated that cracks, 1 in. or more in width should be considered for other repair. Thus, it is not clear how to treat cracks, ½ in. or more and 1 in. or less in width.

2.3 Other State Practices

Specifications and manuals of other state departments of transportations (DOT) in 49 states (Hawaii excluded) have been reviewed in 2012 to find how crack sealing practice varies by state and which type of sealant and filler are used. In addition, approved or qualified product lists have also been reviewed in case sealant and filler are not specified in specifications. The critical findings are listed below:

- Among 49 states, 26 state agencies (53%) had crack sealing/filling in their specifications and/or manuals.

TABLE 2.1
Comparison of Section 408 between the 2012 and 2016 INDOT Standard Specifications.

Section	2012 INDOT Specification	2016 INDOT Specification
408.1	This work shall consist of sealing longitudinal and transverse cracks and joints in existing asphalt pavement in accordance with 105.03	This work shall consist of sealing or **filling** longitudinal and transverse cracks and joints in existing asphalt pavement in accordance with 105.03. **Full lane width transverse cracks and longitudinal joints shall be routed and sealed. All other cracks shall be filled**
408.2	Asphalt Binder for Crack Sealing, PG 64-22 Asphalt Emulsion for Crack Sealing, AE-90, AE-90S, AE-150	**Asphalt Binder**, PG 64-22 Asphalt Emulsion for **Crack Filling, AE-90S**
408.3	A distributor in accordance with 409.03 shall be used when crack sealing and an indirect-heat double boiler kettle with mechanical agitator shall be used when routing and filling. Air compressors shall be capable of producing a minimum air pressure of 100 psi (690 kPa)	A distributor in accordance with 409.03 shall be used when crack **filling with asphalt emulsion** or an indirect-heat double boiler kettle with mechanical agitator shall be used **when filling with hot poured material. An indirect-heat double boiler kettle with mechanical agitator shall be used when routing and sealing**. Air compressors shall be capable of producing a minimum air pressure of 100 psi.
408.5	Cracks and joints shall be routed when specified, with a routing machine capable of cutting a uniform shape to form a reservoir not exceeding 3/4 in. (19 mm) wide with a minimum depth of 3/4 in. (19 mm). The operation shall be coordinated such that routed materials do not encroach on pavement lanes carrying traffic and all routed materials are disposed of in accordance with 104.07. Cracks and joints shall be filled with hot poured joint sealant to within 1/4 in. (6 mm) of the surface in accordance with the manufacturer's recommendations.	Cracks and joints, **1/2 in. or less** in width, shall be routed with a routing machine capable of cutting a uniform shape to form a reservoir not exceeding 3/4 in. wide with a minimum depth of 3/4 in. **Cracks and joints shall be cleaned by blowing with compressed air or by other suitable means**. The operation shall be coordinated such that routed materials do not encroach on pavement lanes carrying traffic and all routed materials are disposed of in accordance with 104.07. Cracks and joints shall be **sealed** with hot poured joint sealant to within 1/4 in. **below** the surface in accordance with the manufacturer's recommendations.
408.6	Cracks and joints shall be cleaned by blowing with compressed air or by other suitable means. Asphalt material shall be placed utilizing a "V" shaped wand tip, to allow the penetration of the materials into the cracks and joints. The cracks and joints shall be completely filled or overbanded not to exceed 5 in. (125 mm), or as required. All excess asphalt material shall be removed from the pavement. The sealed cracks and joints shall be covered with sufficient fine aggregate to prevent tracking of the asphalt materials. All excess cover material shall be removed from the pavement.	**Cracks shall be cleaned** by blowing with compressed air or by other suitable means. Asphalt material shall be placed utilizing a "V" shaped wand tip, to allow the penetration of the materials **into the cracks. The cracks** shall be completely filled or overbanded not to exceed 5 in., or as required. All excess asphalt material shall be removed from the pavement. **The filled cracks shall** be covered with sufficient fine aggregate or **other suitable material** to prevent tracking of the asphalt materials. All excess cover material shall be removed from the pavement **within 24h, when directed**.
408.8	Cracks and Joints in Asphalt Pavement, Seal	Cracks in Asphalt Pavement, **Fill**

17 of 26 state agencies distinguished crack sealing/filling applications as specified in SHRP manual of practice.

- 19 state agencies out of 26 specifically required cleaning of cracks prior to the application of sealant and filler and 17 state agencies also required routing.
- According to ASTM D 6690 standards, crack sealants are categorized into four types (Type I, Type II, Type III, and Type IV) based on their low temperature related performances. Type I is capable of maintaining its effectiveness in moderate climates and Type IV is suitable for very cold climate. However, literature review revealed that state agencies often use multiple types of crack sealants regardless of their climatic conditions. For example, New Mexico uses type IV product and Ohio uses all four types of products. It was interesting to note that a survey conducted in 1992 also showed that state agencies used multiple types of products regardless of their climatic conditions (Eaton & Ashcraft, 1992).
- Regarding requirements for sealant and filler, 13 state agencies specified the type of sealant and filler for crack sealing/filling application. Type II and Type IV crack sealant, based on ASTM D 6690 (2007) classification were the most popular products.
- 17 state agencies had sealants and fillers in their approved or qualified products lists. Although a few states only specify the manufacturer or supplier, others provided a detailed list of products. A total of 74 different products were identified in the list, as shown in Table 2.2. It should be noted that the list included many product types only available locally. Most popular products were the following:

  - Road Saver (Crafco Inc.)
  - Deery (Crafco Inc.)
  - Dura-Fill (P & T Products)
  - Sealtight (W. R. Meadows)
  - D 3405 (Right Pointe)

In summary, the review shows that information was not sufficiently provided regarding sealant and filler. Almost half of the state agencies in the nation either did not include crack sealing/filling application in

TABLE 2.2
List Sealant and Filler Identified from Approved/Qualified Product List (2012).

Manufacturer	Product	Manufacturer	Product	Manufacturer	Product
American Permaquik Inc.	Permaquik 6190 Type I	Dalton Enterprises, Inc.	Crack-Rite HP 3405	P & T Products	Crackmaster 3405 LM
American Permaquik Inc.	Permaquik 6195 Type I	Deery American Co.	Deery 102	P & T Products	Dura-Fill 3405
American Permaquik Inc.	Permaquik 6195 Type II	Deery American Co.	Deery 301 C	P & T Products	Dura-Fill
Bitumar Inc.	Superflex 100	Eagle Asphalt Products	ASTM D 3405 Sealant	P & T Products	Dura-Fill 1109
Colas	ColJoint 6690, Type II	Ergon-Armor	Blackhawk d200	Poly-Carb, Inc.	Poly-Carb Mark-89 Ureshield
Colas	ColJoint 6690, Type IV	Fibrecrete Tech. LLC	Fibrecrete 6690G, Type II	Right Pointe Company	Type I Joint and Crack Sealer
Crafco Inc.	Crafco Road Saver 34211 Type I	Golden Bear of Witco	CRF Crack Filler	Right Pointe Company	ASTM D 3405 Sealant
Crafco Inc.	Deery 103	Koch Materials Co.	Koch #9005 Type I	Right Pointe Company	D-3405 NJ
Crafco Inc.	Asphalt Rubber Plus 241	Koch Materials Co.	Koch #9005 Type II	Right Pointe Company	D-3405 NY
Crafco Inc.	Road Saver 201, 221, 222	Koch Materials Co.	Koch #9005 Type III	Right Pointe Company	Polyfiber-Firm
Crafco Inc.	Crafco Road Saver 34221 Type II	Maggison Ent.	Megaseal Type III 453	SealMaster	CrackMaster 1190
Crafco Inc.	Deery 102	Maxwell Product Inc.	Elastoflex	Ten Cate Nicolon	MiraSeal Elastometric
Crafco Inc.	Flex a Fill 9005	Maxwell Product Inc.	Elastoflex 61	The Pavement Depot	HP3405 Type I
Crafco Inc.	Road Saver 211	Maxwell Product Inc.	Nuvo 3405	The Pavement Depot	HP3405 Type II
Crafco Inc.	Deery 101	Maxwell Product Inc.	Nuvo 6690 Type II	Tremco Inc.	PQ 6190 LM
Crafco Inc.	Road Saver 231	Maxwell Product Inc.	Elastoflex 71	Tremco Inc.	Tremco PQ-6190 LM Type II
Crafco Inc.	Crafco 34540	Maxwell Product Inc.	Elastoflex 500	Ultraseal Const Prod Ltd.	Ultraseal
Crafco Inc.	Deery 103 - 25F	McAsphalt Industries Lmt.	Beram 195 Type II	Unique Paving Materials	Koldflo
Crafco Inc.	Road Saver 231	McAsphalt Industries Lmt.	Beram 195 Type III	W. R. Meadows	Hi-Spec Type I
Crafco Inc.	Deery 101 ELT	McAsphalt Industries Lmt.	Beram 195 LM	W. R. Meadows	Sealtight 3405 Plymeric
Crafco Inc.	Roadsaver 522	McAsphalt Industries Lmt.	Beram 30/60 LM	W. R. Meadows	Hi-Spec Type II
Crafco Inc.	Deery 200	McAsphalt Industries Lmt.	Beram 190	W. R. Meadows	Hi-Spec Type III
Crafco Inc.	PolyFlex Type III	Monsey Bakor Inc.	590-13P	W. R. Meadows	Sealtight Hi-spec
Crafco Inc.	Roadsaver 520	P & T Products	Dura-Fill 3405	Western States Asphalt	Rubberized Asphalt Crack Sealant
DAI Emulsions	C-23	P & T Products	Crackmaster 3405		

their specifications or did not have manuals. It was also found that many specifications had not been updated. A few state agencies specifications were based on ASTM D 3405, which expired in 2002, and was subsequently replaced with ASTM D 6690-12 in 2012.

2.4 Available Guidelines of Crack Sealing/Filling

There are a few guideline or manuals available for crack sealing/filling application. Those guideline or manuals include topics such as crack evaluation, planning and design, construction, and performance evaluation. Strategic Highway Research Program first published the manual, "Materials and procedures for sealing/filling cracks in asphalt-surface pavements (SHRP-H-348)" in 1993; the update of the manual was published in 1999 under the same title. There are also detailed guidelines or manuals available from state agencies and the list is provided below.

- *Texas:* Field Manual for Crack Sealing in Asphalt Pavements
- *California:* Caltrans Flexible Pavement Materials Program: Chapter 3 crack sealing, crack filling & joint sealing of flexible & rigid pavements
- *Michigan:* Sealing/filling of cracks for bituminous concrete pavement: selection and installation procedures
- *Montana:* Crack seal manual
- *Nebraska:* Pavement Maintenance Manual

2.5 Crack Sealing/Filling Performance Studies

Several researches have been conducted regarding effectiveness of crack sealing/filling, effectiveness of routing, sealant and filler performance, and equipment and construction. The summaries from the literature review are presented in this chapter.

2.5.1 Effectiveness of Sealing/Filling

Masson (1997) conducted a study regarding effectiveness of sealing of pavement cracks in Canada. The study reported that crack sealing/filling, if applied correctly, is believed to reduce pavement deterioration by minimizing the infiltration of foreign objects (e.g., moisture and incompressible materials) into a pavement structure; thus extending the pavement life. Additional benefits may also include: (1) unit cost of the treatment is less than 6% of patching and (2) a general method of installation is also very simple which involves cleaning the crack using compressed air followed by the application of sealant and filler (Masson, 1997).

The study by Sharaf and Sinha (1986) presented that when more crack sealing was performed in the autumn, less patching was required in the winter in Indiana. Fang et al. (2003) conducted the study for evaluating the cost-effectives of joint/crack sealing in Indiana. Nineteen test sites were selected and both sealed and unsealed sections in each test were constructed and monitored for 2-year period. International roughness index (IRI), falling weight deflectometer (FWD), and condition survey were utilized for pavement performance monitoring. The result showed that there were no significant differences between the performance of sealed and unsealed sections (Fang et al., 2003).

The most critical benefit for the crack sealing/filling applications is a pavement quality improvement and a pavement service life extension. Numerous researches have been conducted regarding the crack sealing/filling performance. However, limited literatures are available for the sealing/filling evaluation with an overall pavement performance perspective.

Rajagopal (2011) conducted a research study for Ohio DOT regarding the effectiveness of crack sealing on pavement serviceability and life, which evaluated the performance of crack sealed pavements in terms of pavement condition rating (PCR), calculated based on the distress data. The study concluded that the crack sealed pavements exhibited better performance than the untreated section on a 5-year life cycle (Rajagopal, 2011). The study did not evaluate an effectiveness of crack sealing on pavement structure condition and rideability. Also, Ong et al. (2010) evaluated short- and long-term effectiveness of pavement preservation treatments in Indiana using the pavement condition data, traffic data, and work information from the Indiana pavement management system. From the study, it was found that crack sealing provided no significant improvement in International Roughness Index (IRI) of pavements (Ong et al., 2010). However, more recent study from Lu and Tolliver (2012) on short-term effectiveness of pavement treatment in IRI, based on LTPP data, reported that crack sealing application offered a significant pavement performance jump in terms of IRI down to 28 in./mile.

2.5.2 Effectiveness of Routing

Shuler (2009) provided the performance of three crack sealants from different manufacturers during a two-year experiment, conducted in Colorado. Most crack sealants failed after only one winter; however, the sealants showed a tendency to heal themselves after 12 months and 21 months. Routing provided the best performances when accompanied with overbanding. Cracks applied without flush seal or overbanding produced the poorest performances (Shuler, 2009).

Masson (1997) investigated the effect of a router on the asphalt over concrete pavement in Canada and reported that micro-cracks appeared at the bitumen aggregate interface and within aggregates themselves after routing. It was further noted that the propagation of micro-cracks upon freezing and thawing was also observed by a magnified view of the sealing-asphalt concrete interface.

Al-Qadi et al. (2015) provided the result from a recent Illinois study conducted in seven different states (i.e., Minnesota, Wisconsin, Illinois, Ontario (Canada), New York, Virginia, and New Hampshire). The study conducted by Illinois concluded that rout and seal application (i.e., crack sealing) is recommended as an effective treatment approach and working cracks are not suitable for clean and seal (i.e., crack filling).

2.5.3 Sealant and Filler Performance

A JTRP study regarding hot pour crack sealant was initiated as an implementation effort for INDOT in 2001. After monitoring various aspects of the trial implementation for several years, the study reported that oil jacketed melters had considerable maintenance problems. In addition, the implementation proceeded at a slow rate. Field inspections revealed that some crews conducted crack sealing operations improperly; as a result, there was large variability amongst crews regarding production and quality (Ward, 2001).

Yildirim, Korkmaz, and Prozzi (2006) conducted a research study to compare the cost-effectiveness, performance, and life-cycle costs for hot pour rubber asphalt crack sealant and cold pour asphalt emulsion crack sealant in Texas. The comparison includes seven different crack and joint sealants: three cold pour and four hot pour rubber sealants. The surveys and field study from 33 different sections indicate that hot pour rubber sealants performed better than cold pour sealants. The cost analyses showed that the overall average annual cost (AAC) for cold pour materials is \$0.107/ft with a standard deviation of 0.06, and for hot pour materials, the average AAC is \$0.045/ft with a standard deviation of 0.042 (Yildirim et al., 2006).

Erickson (1992) performed a one-year performance evaluation of four crack sealants in Washington State. The products include two rubber-asphalt products and two emulsified asphalt cements. As a result, rubber-asphalt products performed better than the other two products. It was also noted that the emulsified products should only be used where an overlay is scheduled in the near future.

Marks (1990) evaluated the low modulus sealant (LMS) from W. R. Meadows and other conventional crack sealants over the 4 year period in Iowa. The LMS performed better for the first two years without exhibiting any failures and also performed better for the entire experiment period.

Zinke and Mahoney (2006) conducted field evaluations of emulsion and hot pour crack sealant on Connecticut secondary roads. The field evaluation consisted of a visual inspection which showed that the hot pour crack sealants performed better than the emulsion in moving cracks (transverse cracks). These results coincided with the findings of research conducted by Yildirim and Prozzi (2006) in Texas.

During the literature review, the survey results regarding crack sealant usage in the states (Eaton & Ashcraft, 1992) was found, as shown in Figure 2.1. The figure shows the different climatic zones in the states, and it can be seen that different type of sealants were used by each state in the same climatic zone. In addition, emulsion was more widely used in early 1990s in which the survey was conducted.

2.5.4 Equipment and Construction

Masson (1997) conducted a study regarding the effectiveness of sealing of pavement cracks in Canada. The study reported that the performance of a sealant is governed by the sealant aspect ratio and the magnitude of the movements. The performance of sealants can be improved by routing cracks so that the WH (width and height) ratio is increased. That is because as the WH ratio increases, the tensile stresses experienced by the sealant onto the interface decrease. However, the field performance showed that 40 mm by 10 mm routs performed worse than that of 19 mm by 19 mm or 12 mm by 12 mm. It is likely that the wider a sealant, the more exposed it is to tires and the more exposed it is to shear stresses (Masson, 1997).

Masson and Lacasse (1999) also investigated the effect of a hot-air lance on crack sealant adhesion in Canada. The finding from the study showed that the hot-air lance slightly affects the adhesion; however, the general condition of the routed surface is more important. During normal heating, the rout temperature increased up to 200°C and did not oxidize bitumen. The lab test (i.e., tensile test) showed that a hot-air lance did not improve sealant adhesion when applied to a dry crack. In addition, the adhesion strength was often reduced by 50% when overheated.

Marquart (2001) conducted an experiment to evaluate the effective sealant capabilities of four Crafco

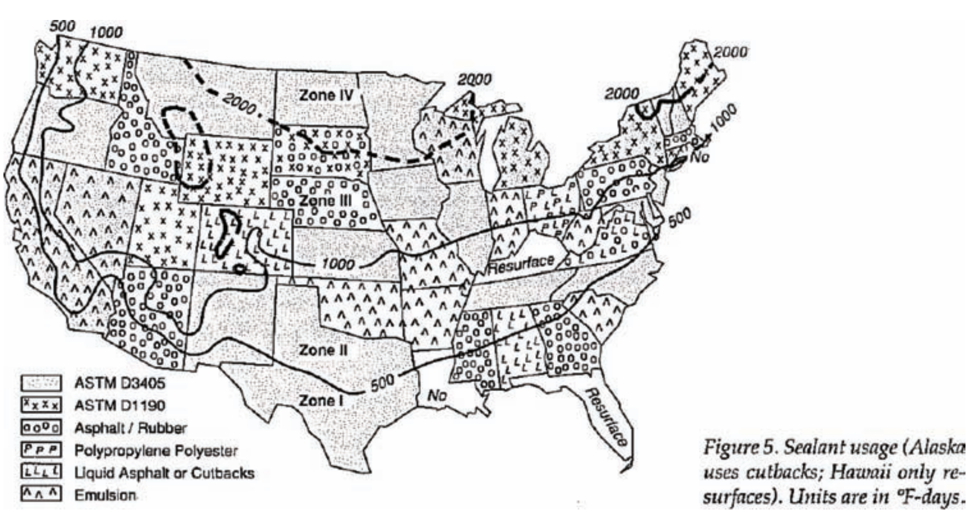


Figure 2.1 State-of-the-art survey of flexible pavement crack sealing procedures in the United States (Eaton & Ashcraft, 1992).

crack sealing products (Crafco 34221, 24522, 35240, and 34231) in North Dakota. It was found that the majority of the failures (85%) were due to missing of or near missing the crack during the routing process. Consequently, properly routed cracks performed better. All Crafco sealants were deemed to be able to expand with the crack movements in the test sections (Marquart, 2001).

2.6 Evaluation Methods for Crack Sealing/ Filling Performance

2.6.1 Field Test

2.6.1.1 Visual Inspection. Yildirim and Prozzi (2006) compared performances of a hot pour rubber asphalt crack sealant and cold pour asphalt emulsion crack sealant in Texas. They evaluated the performance using a visual inspection on sealed cracks. More details about their study are the following:

- Types of failures monitored in the inspection:
  - Open previously sealed cracks
  - Adhesion loss
  - Cohesion loss
  - Loss of seal in previously sealed cracks
  - Settlement and bleeding of sealants
  - Pullout of material
  - Spalls or secondary cracks in or near the sealed crack
  - Other distresses in or near the sealed crack
- Settlement and bleeding of sealants were measured as settlement is common for cold pour sealants.
- Height of the hot poured sealant was measured as they are critically important in terms of ride quality.
- Treatment effectiveness was calculated using percent failure. Percent failure was obtained by dividing failed length of sealed cracks by total length of sealed cracks.

The National Transportation Product Evaluation Program (NTPEP), under the American Association of State Highway and Transportation Officials (AASHTO), evaluated sealants and fillers to share their performance results with state DOTs. The evaluation method includes ASTM laboratory tests and field evaluations based on a manual of practice by the Strategic Highway Research Program (SHRP). The field evaluation procedures are the following (AASHTO, n.d.):

- Field evaluation involves the following type of observations:
  - *Water infiltration:* water infiltration will be measured as the percentage of the overall crack length where water can bypass the sealant and enter the crack either through complete adhesion or cohesion failure.
  - *Debris or Stone Retention:* debris of stone retention will be rated based on their severity based on visual inspection (No, Low, Medium, and High severity).
  - *Spalling:* spalling is defined as the length of any cracking, breaking, chipping or fraying of crack edges. The length and severity of spalling will be measured along each crack.
  - *Crack Movement:* longitudinal and transverse crack movements shall be measured by installing pins or PK nails on both sides of three transverse and longitudinal cracks.
  - *Crack Spacing:* crack spacing is acquired from the crack mapping.
  - *Photo Log:* photographs of the cracks are taken.

2.6.1.2 Bonding Strength. Yildirim and Prozzi (2006) evaluated bonding between the sealant and pavement by pulling out the sealant from the pavement using a pointed tool in Texas. The easiness of pulling sealant was rated as "Easy," "Medium," or "Difficult."

2.6.1.3 Smoothness. Erickson (1992) conducted a research on effectiveness of crack sealing in Washington and measured the smoothness of the asphalt concrete pavement using a roughness meter. The result indicated that the smoothness was effective in distinguishing between the crack sealed and non-crack sealed sections.

2.6.2 Laboratory Test

2.6.2.1 Application Characteristics. The viscosity of crack sealant and filler is one of the factors affecting the initial bonding between the materials and the asphalt pavement surface. Thus, it is imperative that the materials are applied at the appropriate viscosity for better performance. ASTM D 4402 (2013) is used to measure the apparent viscosity of asphalts at handling, mixing, or application temperatures. The test method utilizes a rotational viscometer and a temperature-controlled thermal chamber for maintaining the test temperature varying from 38°C to 260°C. Al-Qadi, Fini, et al. (2008) came up with the test procedure and equipment to correctly simulate the shearing of the material during the installation in the field. The recommended setting was SC4-27 spindle at a speed of 60 rpm (shear rate of 20.4 s-1) as the size allows for a wide-range of shear rates (from 0.08 to 93.0s-1) in the test.

2.6.2.2 Adhesion. The adhesive property of crack sealant and filler for asphalt concrete pavements is normally evaluated using ASTM D 5329 (2009), which includes two test methods: the bond test and the asphalt compatibility test. The bond test is to assess the ability of the material to maintain a proper adhesion by measuring the bond strength to a concrete block. The asphalt compatibility test is to evaluate the compatibility with an asphalt pavement. It should be noted that the results from both test methods are not quantitative, but qualitative (e.g., pass or fail).

Al-Qadi, Masson, Yang, Fini, and McGhee (2009) reported that there was no indication of any correlation between the results of ASTM test methods and the field performance for sealants. In order to select the best performance correlated test method, the study evaluated three other different laboratory test methods: (1) the adhesion work test measuring the free energy of bond; (2) the direct tension test (DTT); and (3) the fracture test. As a conclusion, DTT was determined to be best suited (Al-Qadi et al., 2009).

2.6.2.3 Extensibility. A material's extendibility indicates an ability to release stress at low temperatures. In other words, the extendibility represents how fast a material can dissipate an imposed loading. Al-Qadi et al. (2008b) evaluated three performance parameters at low temperature: extendibility, modulus reduction percentage after 10s of loading, and strain energy density using the crack sealant direct tension test. They found that the extendibility was a good criterion for identifying and distinguishing performance at low temperature among sealants.

2.6.2.4 Flexibility. Al-Qadi et al. (2008a) reported that a key to crack sealant and filler durability is how well the material maintains its rheological properties. The standard flexibility test is available in ASTM D 5329 (2009). Al-Qadi et al. (2008a) found an inability in the current ASTM testing procedures to provide a good indication of field performance. As a result, they proposed the modified Bending Beam Rheometer (BBR) test to measure the flexural creep at temperatures between – 4°C and – 40°C. The crack sealant bending beam Rheometer test utilizes a much thicker specimen because the crack sealant and filler experiences an excessive deflection than asphalt binder used for the PG testing.

3. SURVEY OF CRACK SEALING/ FILLING PRACTICE

3.1 Plan

Knowing a nationwide practice of crack sealing/filling was imperative in understanding a relative practice level of the INDOT crack sealing/filling and planning the evaluation methodology in this study.

A nationwide survey was conducted in 2012, which consisted of four categories of questions: material, construction practice, performance, material selection criteria, and compatibility issues with other pavement preservation treatments. In total 17 responses were received, as shown in Figure 3.1. State or province in a circle indicates from which the responses were received. In the figure, the states where crack sealing/filling are specified in the specification is indicated as S, and the states where sealant or filler are included in the product list is indicated as P. Seven of seventeen responses were from states where neither manual nor specification was available for crack sealing/filling, thus, the survey provided information which were not available from the specification review.

3.2 Nationwide Survey

3.2.1 General

According to the 17 responses to the survey, only two state agencies differentiate between crack sealing and filling activities as they were defined the manual of practice from Strategic Highway Research Program (SHRP). It was interesting to note that Connecticut uses the terminology, "Fill," as crack treatment constructed before the overlay and the terminology, "Seal," as crack treatment without overlay. Louisiana and Florida perform neither crack sealing nor filling.

Regarding the routing, only 7 out of 17 states responded that they do require routing in crack sealing/filling. According to the literature review of specifications and manual, 17 out of 26 states required routing.

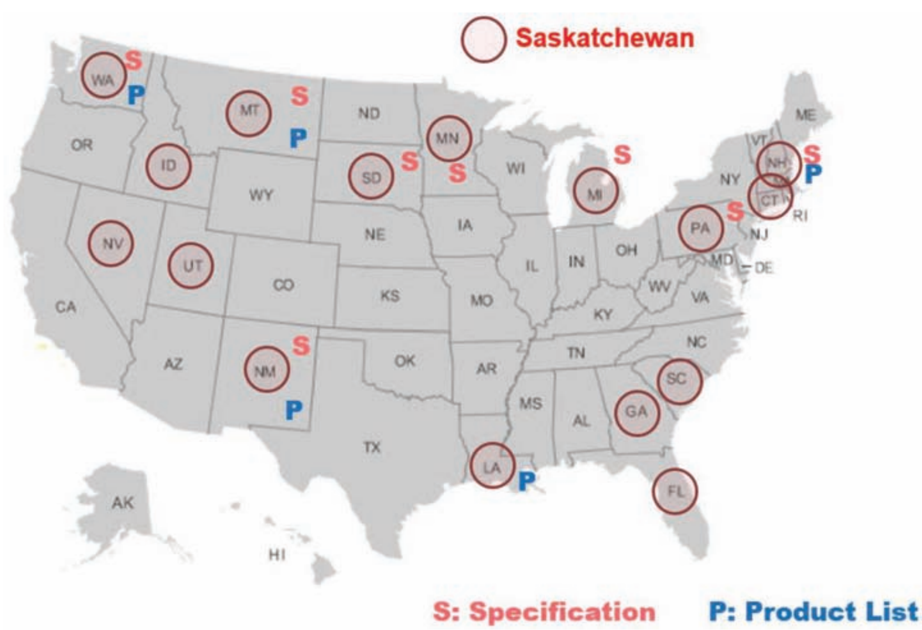


Figure 3.1 List of states responded to the survey.

3.2.2 Materials

The sealants are classified into four types (ASTM D 6690, 2007) and the usages by state are shown in Figure 3.2. ASTM D 6690 classifies hot poured crack sealant into four different types based on their low temperature performances: Type I for moderate climate; Type II and III for most climates; and Type IV for very cold climate. Type II sealant was the most widely used, and products from Crafco, Deery, and McAsphalt were the most popular manufacturers among the states. Ohio and Missouri indicated that they apply all four types. Alaska and New Mexico included Type I and Type IV, respectively. These responses indicating that, in general, there was no pattern of the types used in terms of climate condition.

All responses noted that the performance was the most critical factor in sealant and filler selection. Other factors considered in sealant and filler selection were availability and price. It was interesting to note that New Hampshire would only use products tested by NTPEP effective in 2013. The NTPEP does not recommend any material to users, but provides test results.

3.2.3 Compatibility

Next question was regarding compatibility issues between any asphalt surface treatment (e.g., seal coat, microsurface, overlay, etc.) and crack sealant and filler. The notable findings are provided in the below:

- *Michigan:* bleed through of crack filling material on chip seal projects.
- *Montana:* in case of overlaying a crack sealed road, the mix can "slip" on the crack seal rubber, creating a bump in the surface. We can prevent this with an isolation lift.
- *Pennsylvania:* sometimes when placing hot mix the heated asphalt causes the sealant material to expand or bubble up.
- *Saskatchewan, Canada:* rubber asphalt crack sealing (RACS) and thin lift overlays: asphalt not adhering to rubber.

3.2.4 Others

Other interesting findings from the survey are summarized in the following:

- *Michigan:* the contractors are allowed to selects materials from a list for crack fill warranty contract.
- *New Hampshire:* "fibered" crack sealant are specified to be applied when micro-surfacing will be applied and the results were good.
- *New Mexico:* wait at least 6 months before doing a surface treatment over a crack seal.

3.3 Indiana Statewide Survey and Interview

An Indiana statewide survey was conducted in 2012 among 29 Sub-districts in six Districts (e.g., Crawfordsville, Fort Wayne, Greenfield, La Porte, Seymour, and Vincennes). In addition, the research team conducted on-site interviews with engineers and operation managers from maintenance units and Sub-district offices in Fowler, Columbus, Monticello, Winamac, and Fort Wayne in spring 2013.

The survey consisted of five categories of questions: planning, material, construction, equipment, and performance/safety. Nineteen of 29 Sub-districts responded to the survey as shown in Figure 3.3. It should be noted that 26% of the responses were incomplete. As a result, partial information was chosen

Figure 3.2 Hot poured crack sealant usage by ASTM D 6690-12 (2012) type in the states.

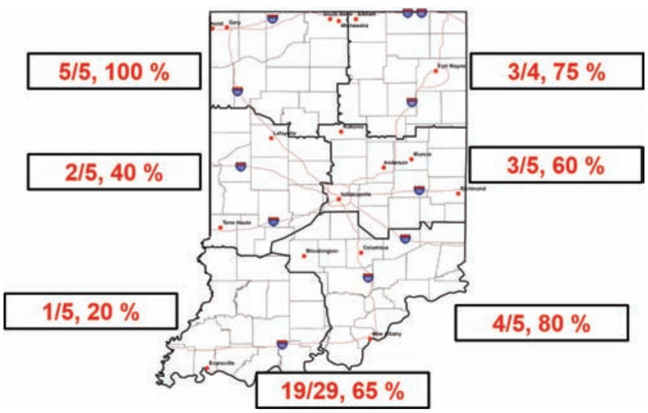


Figure 3.3 Response rate to the survey by District in INDOT.

from the uncompleted responses for a survey result analysis. The major findings from both survey and site interview along are presented in the subchapters.

3.3.1 Planning

A visual inspection was only used in deciding sealing/filling candidates. Sealing for moving cracks (e.g., transverse crack) and filling for non-moving cracks (e.g., longitudinal crack) were applied. The survey indicated that they typically reseal any roads, which were sealed or filled before and no known issues have been reported with the resealing.

In order to estimate the amount of material to be used for sealing/filling application, most Sub-districts refer to their historical data. The others noted that approximately 1000 lbs to 2000 lbs of AE-90S per lane mile for crack filling and 500 lbs to 1500 lbs of crack sealant per lane mile for crack sealing are required.

3.3.2 Material

The most Sub-districts responded to the survey that AE-90S has been exclusively used for crack filling application and the ASTM Type II sealant has been widely used for crack sealing. It was found that different products were used by each Sub-district at the time of the interview. For example, Fowler Sub-district used products from McAsphalt and RightPointe, on the other hand Columbus, Monticello, and Winamac Sub-district used Crafco products. Later, it was found that different product was purchased for each year and left over materials are reused in the following season. RoadSavor 201 from Crafco, 3405 Reg. from Right Pointe, and Beram 195 from McAsphalt were used in the following periods: 2010 to 2012, 2012 to 2013, and 2013 to 2014, respectively. It should be noted that there were various unit prices due to various order quantities from Districts.

3.3.3 Construction

While crack sealing is constructed all year around, it was reported that May was the most popular month. Crack filling, however, was typically constructed through November to April: there were no responses of crack filling in June, July, and August. It should be noted that the INDOT (2014) Standard Specification limits sealing or filling operations when the ambient temperature is below 40°F. The typical reservoir dimension used in the Sub-districts was ¾ in. by ¾ in. and the other dimension was ½ in. ~ 1 in. by ½ in. ~ 1 in.

Production rates were between four to six lane miles per day for crack filling and two to four lane miles per day for crack sealing. The lower production rates of crack sealing are due to the fact that the crack sealing operation requires the routing. For the configuration of crack sealing/filling, "Overband" was the most popular choice.

3.3.4 Equipment

Most widely used sealant kettle was from STEPP MFG., which is an oil jacketed sealant kettle (i.e., heating by circulating a heated fluid), as shown in Figure 3.4 (a). The 250 gallon capacity model usually required a heat-up time up to four hours before the crack sealant reaches to the manufacturer's recommended installation temperature. Many Sub-districts responded that an availability of the sealant kettle is one of major issues as typically only one sealant kettle is available for each District and Sub-district should share it. From this research, it was reported that newer model may drastically reduce the heat-up time as much as less than one hour. In addition, air compressor is equipped with the new sealant kettle model, so there is no need for a truck and a driver for an air compressor unit required for the crack sealing/filling installation.

Indiana uses two fuel types for emulsion kettles: propane-heating and diesel-heating types. The propane-heating emulsion kettle, as shown in Figure 3.4 (b), is mostly used in Indiana. STEPP MFG. was also the most popular manufacturer of emulsion kettles. Heat-up time was about one hour as the application temperature of emulsion is much lower than the crack sealant application temperature.

All routers used in INDOT are manually operated, as shown in Figure 3.4 (c). The router operation itself is labor intensive activity as well as the router is prone to cause downtimes due to the mechanical issues. It was reported that routing activity is believed to be the dominant factors affecting the lower production rates of crack sealing than that of crack filling. A new type of router, RapidRouter™ (RR), was discovered during the site interview. RR is a skid steer mounted router, so it requires skid loader and two operators. It should be noted that a lot of safety concerns were expressed regarding the router operation especially when the router is operated near a center lane. This research had an opportunity to evaluate the RR and its result is presented in the later chapter.

According to the INDOT (2014) Standard Specifications, air compressors for the crack sealing/filling installation should produce a minimum air pressure of 100 psi. All air compressors reported in

Figure 3.4 Crack sealing/filling equipment: (a) sealant kettle; (b) emulsion kettle; (c) manual router; (d) air compressor; (e) V-shape squeegee; (f) straight squeegee.

the survey and inspected during site interview exceeded the requirement. A portable air compressor from SULLAIR, as shown in Figure 3.4 (d), was the most widely used type. A few Sub-districts responded that they have hot air lance, which produces hot air (400°F to 3000°F) to dry moistures from cracks. Additional benefit of the use of a hot air lance is that it would increase the pavement crack temperature to a warmer condition so the crack sealant and filler maintain their application temperature for a longer period of time. In order to confirm the effectiveness of the hot air lance, this research evaluated its performance and provides the results in the later chapter.

INDOT specification does not require specific type of squeegees to be used for the crack sealing/filling installation. From the survey, three types of squeegees were used in the state, such as "V," straight, and "U" shapes. Figure 3.4 (e) and (f) show "V" shaped and straight squeegees, respectively. In order to prevent tracking, sand is generally used as blotting material for AE-90S, and soap water or regular tap water is used as blotting material for hot poured sealants.

4. EXPERIMENTAL EVALUATION OF CRACK SEALING/FILLING EFFECTIVENESS

4.1 Plan

This research mainly performed a comparative study using crack sealing/filling field performance data, including (1) crack sealing/filling sections vs. an untreated (i.e., do-nothing) section for the effectiveness of crack sealing/filling; (2) routed vs. non-routed sections for the effectiveness of routing; (3) crack sealing/filling sections with different materials for sealant and filler material evaluation; (4) Rapid Router™ vs. a conventional manual router applied sections; and (5) Hot air lance vs. a conventional air compressor applied sections. In addition, the research evaluated sealant and filler performance grading testing and correlated it to the field performance to evaluate its necessity of adoption in the INDOT crack sealing/filling practice. An experimental program and selections for test locations, materials, performance test methods, and data collation plan are detailed in the following subchapters.

Figure 4.1 Location of test sections.

4.1.1 Field Test

4.1.1.1 Location. A test section needs to be exhibiting transverse cracks while not having received any kind of pavement preservation treatments so that a test section can be constructed using crack sealant and filler selected for the study. INDOT routinely performs crack sealing/filling treatment on a newly constructed or overlaid pavement within 2 to 3 years. As a result, only a few road sections were available for the study. Two test sections, SR-43 and US-52 in Indiana as shown in Figure 4.1, were selected and each section represents northern climatic and southern climatic conditions, respectively.

SR-43 test section is northbound lane north of Brookston, Indiana, which was milled and overlaid three times in 1984, 1994, and 2010. The road had one lane in each direction and the Average Annual Daily Truck Traffic (AADTT) was 5,528 in 2013 with truck traffic accounting for 16%. Transverse crack spacing ranged from 30 to 100 ft.

SR-52 test section is eastbound lane east of Metamora, Indiana, which was overlaid in 2010. The road had one lane in each direction and the Average Annual Daily Truck Traffic (AADTT) was 3,035 in 2013 with truck traffic accounting for 10%. Transverse crack spacing ranged from 20 ft to 40 ft.

4.1.1.2 Materials. The evaluation included nine sealants and fillers: five sealants and four fillers as shown in Table 4.1. The sealants included Crafco Road Savor 211 for ASTM D 6690 Type I; and Crafco Road Savor 201, RightPointe 3405 Regular, and McAsphalt Beram 195 for ASTM D 6690 Type II; and Crafco RoadSavor 222 for ASTM D 6690 Type III. All sealants have rubber contents ranging from 2% to 18% by volume. The ASTM Type II crack sealants have been recommended for the climate condition of Indiana and McAsphalt Beram 195 and Crafco RoadSavor 201 were included in the qualified product list of INDOT. RightPointe 3405 Reg. was selected as it was one of the most widely used sealants and available in Indiana.

The crack filling materials included Crafco Fiber Asphalt, Crafco Poly Flex, AE-90S, and asphalt PG 64-22 binder. AE-90S is a polymer-modified rapid setting emulsion obtained from Asphalt Materials in

TABLE 4.1
Sealant and Filler Specifications and Costs.

Manufacturer	Product	Application	ASTM D 6690 Type	Rubber Contents	As of 2013 Cost/lb
Asphalt Materials	**AE-90S**	Filling		0%	$0.25
Crafco	**Poly Flex**	Filling		0%	$0.43
Crafco	**Fiber Asphalt**	Filling		0%	$0.43
Crafco	**RoadSavor 201**	Sealing	2	18%	$0.50
Crafco	**RoadSavor 211**	Sealing	1	7%	$0.40
Crafco	**RoadSavor 222**	Sealing	3	2 to 6%	$0.55
McAsphalt	**Beram 195**	Sealing	2	7.5 to 10%	$0.37
Right Pointe	**3405 Reg.**	Sealing	2	10%	$0.46
Crafco	**PG 64-22**	Filling		0%	

Warsaw, IN. AE-90S is widely used for crack filling operation in Indiana due to its workability at low temperatures. In general, the construction season for crack filling using AE-90S is November through March in Indiana. Crafco Fiber Asphalt, Poly Flex, and PG 64-22 binder were recommended by the Study Advisory Committee to evaluate fillers never used in INDOT. Fiber Asphalt is a fiberized crack filling product and generally used as a pretreatment for microsurfacing. Poly Flex is a crack filler with polymers.

Unit prices of sealants and fillers ranged from \$ 0.25/lbs to \$ 0.55/lbs. It should be noted that AE-90S costs about 65% of the average hot poured sealant and filler cost (\$ 0.45/lbs). Considering the residue of AE-90S (e.g., 65%) and the cost of AE-90S (\$0.33/lbs), the cost of AE-90 is compatible to that of the hot poured materials.

4.1.1.3 Construction

4.1.1.3.1 SR-43. Prior to the construction, its existing pavement condition on the sections was investigated. In total, 170 transverse cracks were identified and their digital images with the location information were collected, as shown in Figure 4.2. The test section was determined to be located between R.P. 37 and R. P. 40. The test section was divided into nine 1000 ft long subsections considering crack distribution. Each material was designed to be applied on 1,000 ft long section, which consists of 500 ft long routed and 500 ft long non-routed sections. Each routed section and non-routed section represent crack sealing and crack filling application, respectively. One 500 ft section was prepared as an untreated section (do-nothing section), which was treated with neither crack sealing nor filling.

Crack sealing and filling were constructed on July 22 and 23, 2013. During the construction, air and pavement temperatures were 72°F to 81°F and 82°F to 109°F, respectively. For routed sections, only transverse cracks were routed with reservoir dimension of ½ in. wide and ½ in. deep. The construction procedure for crack sealing application is shown in Figure 4.3. The sealant kettle was emptied before putting different product into the sealant kettle to minimize the cross contamination. It was interesting to note that Monticello Sub-district sprayed water after the placement of sealant to the routed crack to prevent tracking. The conventional method used by INDOT to prevent tracking in sealing application is spraying soap water. The water spraying method seemed to be effective. The treated sections were immediately opened to the traffic and no issues of tracking were noticed. It should be noted that asphalt binder PG 64-22 was not used for the SR-43 test section. The PG 64-22 was added to the study from the SAC meeting after the SR-43 section construction.

4.1.1.3.2 US-52. Prior to the construction, existing pavement condition was investigated. In total, 260 transverse cracks were located. The test section was determined to be located between R.P. 145 and R. P. 153. The crack sealing and filling application requires a traffic control and only straight parts of US-52 section were selected due to safety reasons. As a result, three sections were selected to be the test sections as shown in Figure 4.4.

The test section was divided into nine 1000 ft long subsections considering crack distribution. Each material was designed to be applied on 1,000 ft long section, which consists of 500 ft long routed and 500 ft long non-routed sections. Three test sections were not equal in length, thus different number of products were installed in each section. Specifically, two, four, and three 1000 ft long subsections were distributed for section 1, 2 and 3.

Crack sealing and filling were constructed in October 28~30, 2013. During the construction, air and pavement temperatures were 53°F to 65°F and 54°F to 73°F, respectively. The routed sections were prepared with the

(a) (b)

Figure 4.2 Pre-construction evaluation: (a) example of transverse crack; (b) crack distribution of SR-43 test section.

Figure 4.3 Crack sealing application procedure: (a) routing; (b) cleaning; (c) sealant application; (d) spraying water.

Figure 4.4 SR-52 test sections.

same dimension of ½ in. wide and ½ in. deep and 500 ft long of untreated section (do-nothing section) was also prepared. During the construction, it was noted that AE-90S and PG 64-22 were flowing down the reservoir when applied into cracks on slope.

4.2 Test Methods

4.2.1 Field Test

To evaluate the effectives of crack sealing/filling performance, effectiveness of routing, and the performance of sealant and filler, international roughness index (IRI) for ride quality, FWD for structural integrity, visual inspection for adhesive/cohesive/spalling (ACS) failure, UPV for crack integrity, and permeability for water infiltration were performed.

Five transverse cracks from each 500 ft long section were first selected in random manner and the series of tests were conducted. It should be noted that IRI test was separately performed as the traffic control was not required. The procedures are the following:

- FWD test was first performed as shown in Figure 4.5 (a).
- Then the test location on each crack was marked on the pavement using the template, as show in Figure 4.5 (b), so the subsequent tests could be conducted on the crack and location.
- The digital images of entire crack were then collected.
- Texture scanner was then place on the crack. While the texture scanner was collecting the data, UPV test was performed as shown in Figure 4.5 (c).
- Finally, the flow rate test was performed.
- The same procedure was then repeated for each crack in the test section.

4.2.1.1 IRI. Pavement smoothness is considered a critical factor in evaluating pavement conditions, as it affects the ride quality, and is the most important factor for the traveling public (Decker, 2014). IRI is one of the primary indices used to evaluate pavement smoothness. The profiles in the right wheel path were collected using dot lasers from AMES Engineering with a sampling rate of four samples per ft. Collected data was analyzed using Profile Viewing and Analysis (ProVAL Version 3.40.0297) along with 10-in. moving average.

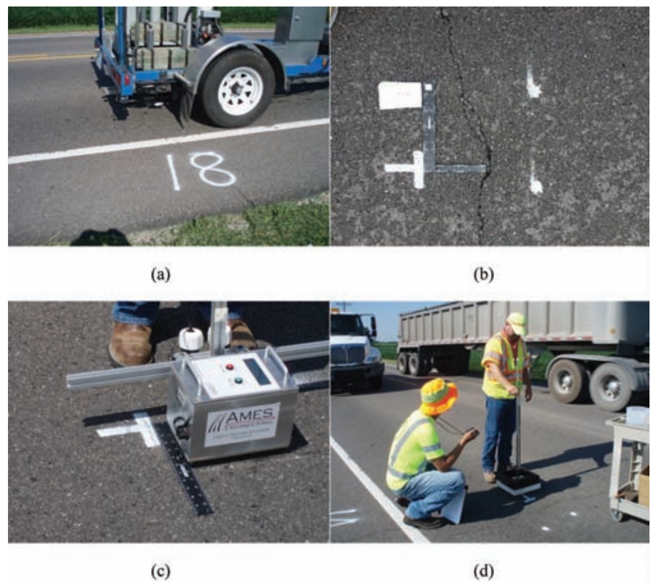


Figure 4.5 Field test procedure: (a) FWD; (b) marking; (c) UPV and texture scanner; (d) flow rate test.

4.2.1.2 Falling Weight Deflectometer (FWD). FWD tests with the 9-kip load level were conducted to evaluate the pavement deflection and Load Transfer Efficiency (LTE). The FWD was positioned in a way that the crack is placed between the weight and the sensor, located 12 in. behind the weight. LTE was then calculated using the Equation 4.1. LTE evaluates how crack sealing/filling affects the crack deterioration.

$$LTE(\%) = \frac{Defection_{12in.behind the weight}}{Defection_{below the weight}} \times 100 \qquad (4.1)$$

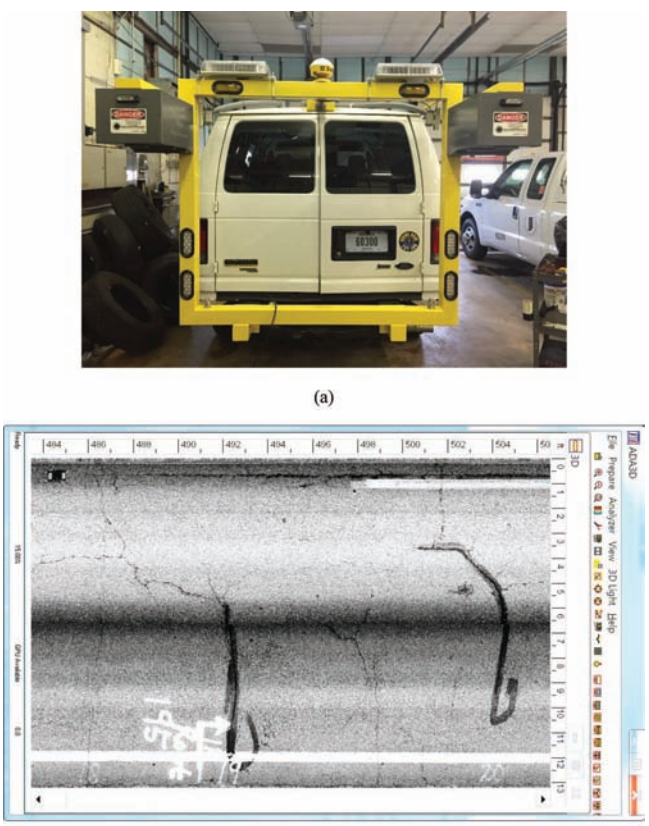
4.2.1.3 Surface Crack Evaluation. Surface crack evaluation was conducted by the digital highway data vehicle (DHDV) with PaveVision3d Ultra from Waylink Systems Co, as shown in Figure 4.6 (a). DHDV is capable of capturing continuous images of full-lane with pavement surface at a high speed (up to

60 mph). DHDV became available in 2015, thus only one set of data was collected in spring 2015, which was 5^{th} data collection for other evaluation methods.

All cracks identified during the preconstruction inspection were treated with either crack sealing or filling during the construction of test sections. Any untreated cracks thus were assumed to have been formed after. Cracks were categorized in terms of distress type: longitudinal crack, transverse crack, and fatigue crack. An example of survey image is shown in Figure 4.6 (b). For the analysis, the length-based measurement was used in order to add up the extents of different types of cracks. In detail, the length-based coverage of longitudinal crack and transverse crack are same as its total length. In case of fatigue crack, only the longitudinal length was calculated. Finally, average crack length was calculated using Equation 4.2.

$$Averagecracklength = \frac{\sum^{L} ength_{longitudinal,transverse,fatigue}}{\sum^{S} ectionLength/100} \tag{4.2}$$

4.2.1.4 Adhesive/Cohesive/Spalling (ACS) Failure. Digital images of cracks were collected and analyzed to evaluate adhesive/cohesive/spalling (ACS) failure.



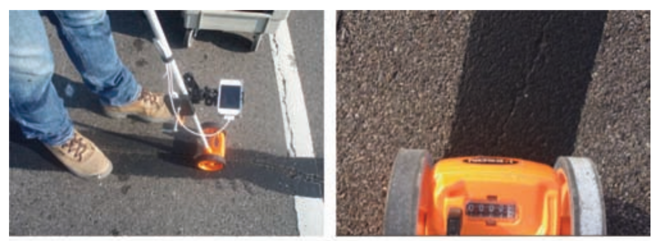
(a) (b)

Figure 4.6 Surface crack evaluation equipment: (a) digital highway data vehicle; (b) sample image.

A digital image acquisition system was developed using a smart phone mounted on a distance measuring instrument, as shown in Figure 4.7. Types and extents of failures (i.e., adhesive, cohesive, and spalling) were visually determined using the digital image of each crack and ACS failure was calculated using Equation 4.3.

$$ACSFailure = \frac{L_{AdhesiveFailure} + L_{CohesiveFailure} + L_{Spalling}}{L_{Crack}} \times 100 \tag{4.3}$$

4.2.1.5 Ultrasonic Pulse Velocity (UPV). The UPV test measures the ultrasonic pulse travel time between a transducer and a receiver through the tested asphalt pavement. The traveling speed of ultrasonic pulse varies by material properties such as crack, density, and stiffness. Ultrasonic test equipment used in this evaluation was Pundit Lab from Proceq. The test instrument consisted of a data acquisition devise, a transducer, and a receiver. A long cone-shaped transducer and receiver using a 45-kHz pulse signal without an ultrasonic couplant were used in this field test. The transducer and the receiver were placed on both cracked and non-cracked pavement surface to measure its travel time, as shown in Figure 4.8. The wider the crack opening and/or the deeper the crack depth, the slower ultrasonic pulse velocity travels.



(a) (b)

Figure 4.7 Digital image acquisition system: (a) data collection and (b) collected image.

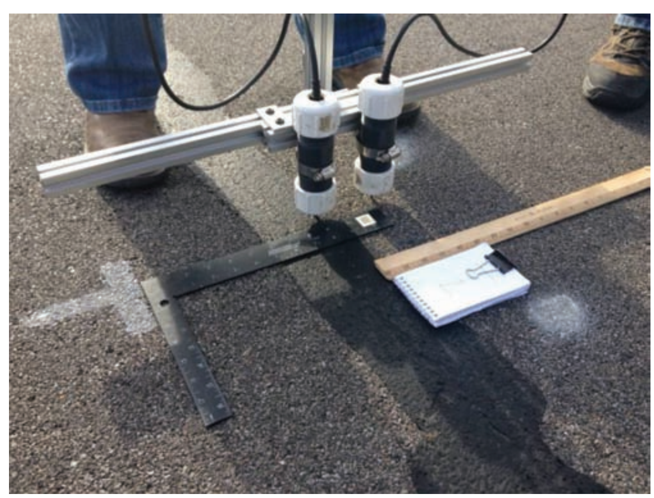


Figure 4.8 Ultrasonic pulse velocity test.

The travel time of ultrasonic pulse velocity is affected by temperature of medium through which it travels, and data collection was conducted under various weather conditions. As a result, Calibration coefficient (0.106 μs/° F) was obtained in the lab by measuring UPV of field core samples at different temperatures. All measurements were calibrated for 70°F.

4.2.1.6 Texture Scanner. Crack width and shape of sealant or filler placed on a crack change due to temperature change. By knowing crack movement of sealant or filler deformation, data regarding how well each sealant or filler resists to the deformation due to crack movement can be collected.

Texture scanner used in the study is the Model 9300 Laser Texture Scanner from Ames Engineering. The texture scanner was originally designed to measure the texture content of any surface and the examples of scanned images are shown in Figure 4.9. The figure shows the each step of sealant procedure images and scanned images obtained by the texture scanner. The texture scanner provided sufficient resolution to show crack shape changes, and the texture scanner also provided raw data, measured distance from the scanner and the surface.

Thus, the reservoir volume could be calculated using Equation 4.4.

$$Reservoir\ Volume = \sum_{line=1}^{11} \sum_{data=1}^{7120} Measurement_{line,data} * 0.00056 * 0.35 \quad (4.4)$$

4.2.1.7 Permeability. One of the main benefits of crack sealing/filling is to prevent water or foreign object from infiltrating into a crack. As a result, most crack sealing/filling researches have adopted visual inspection to monitor any type of defects in the treated crack. However, cracks change its shape and width along with temperature fluctuation and micro-cracks occurred within materials may be difficult to detect only using visual inspection. Thus, permeability test method applicable in the field was developed using a laboratory asphalt permeameter.

The main issue regarding a field permeability test was sealing between the instrument and a pavement surface. The pavement surface has textures, thus it was prone to leaking. As a result, High density foam tape, commonly used for door sealing, was applied at the bottom of the instrument. In order for the foam to tightly conform to the pavement texture, it was decided to put weights on the instrument. The final permeability test procedure is the following:

- Weight is placed to prevent water from leaking, as shown in Figure 4.10 (a).
- Water is filled and the initial height of water in the tube is recorded, as shown in Figure 4.10 (b).
- Road is inserted into the tube to release the stopper, as shown in Figure 4.10 (c).
- Record a time when the height of water reaches to the 0 in the tube, as shown in Figure 4.10 (d).
- Finally, calculate the flow rate (cm/s) using Equation 4.5.

$$FlowRate = \frac{InitialWaterHeight}{Time_{WaterHeightat0}} \quad (4.5)$$

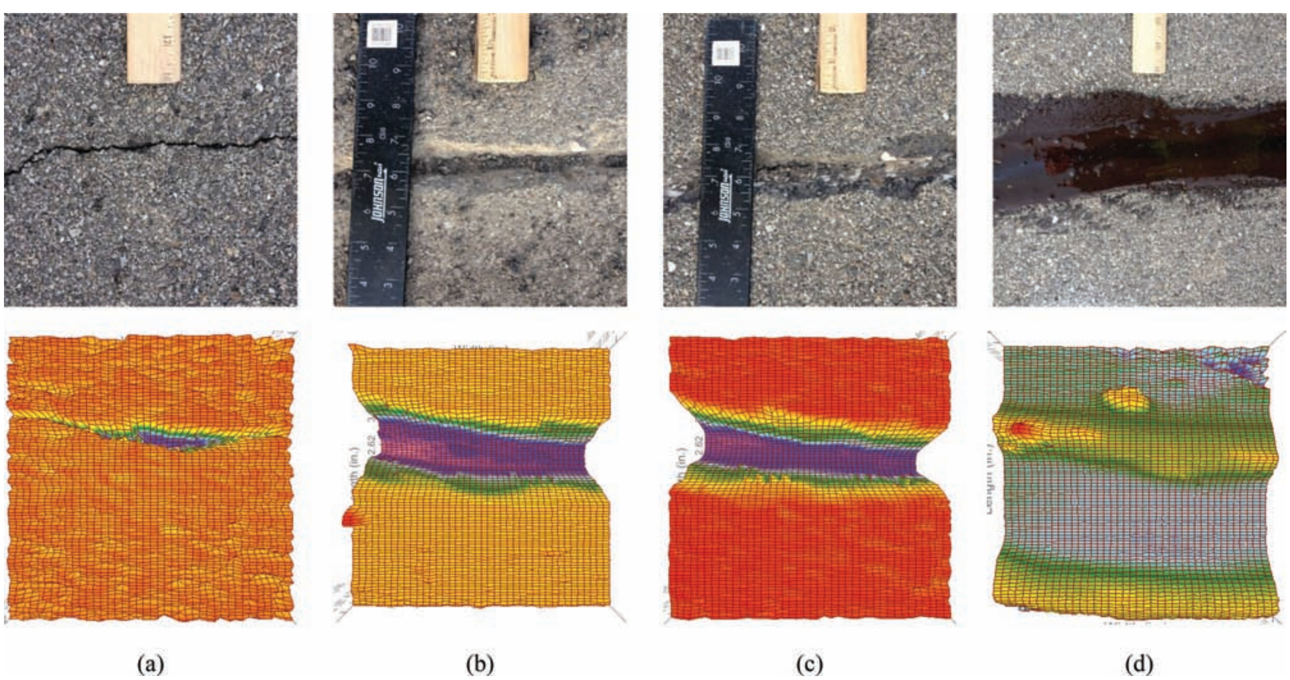


Figure 4.9 Example of texture scanner image: (a) original crack; (b) routed crack; (c) routed crack after cleaning; (d) sealed crack.

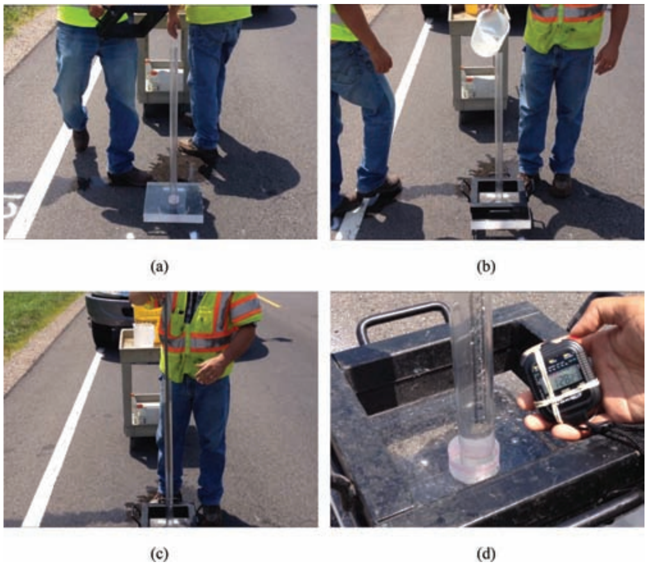


Figure 4.10 Test procedure for permeability test: (a) placing weight; (b) filling with water: (c) releasing the stopper; (d) measuring time.

4.2.2 Laboratory Test

4.2.2.1 Direct Tension Test. A material's ability to relax stress and its extendibility is critical at low temperatures as it determines how fast a material can dissipate an imposed loading (Al-Qadi et al., 2008b). An Illinois study proposed a modified direct tension test, crack sealant direct tension test (AASHTO TP 88), for evaluation of crack sealant and filler behavior at low temperatures. Accordingly, the extendibility of nine sealants and fillers were determined by direct tension test.

4.2.2.2 CSBBR. The key to crack sealant and filler durability is how well the material maintains its rheological properties. According to the study conducted in Illinois, several previous studies had shown the inability of current ASTM test to provide a good indication of field performance. As a result, a modified bending beam Rheometer (CSBBR, AASHTO TP 87) test was proposed to measure the flexural creep at temperatures between –4 and –40°C. The crack sealant bending beam Rheometer test utilizes much thicker specimen due to excessive deflection caused by the crack sealant and filler material compared to that of asphalt binder. Accordingly, flexibility of nine crack sealants and fillers were tested by CSBBR (ASTM D 5329, 2009).

4.3 Results and Analysis

4.3.1 Effectiveness of Sealing/Filling and Routing

The effectiveness of crack sealing/filling and routing practice was evaluated by comparing the performance of crack sealing/filling sections to the untreated sections (i.e., the do-nothing sections). In addition, the effectiveness of routing was evaluated by comparing the performance of the routed and non-routed sections.

Two types of pavement performances were collected over time, such as pavement and crack performances. IRI, FWD, and surface crack evaluation were conducted to assess pavement performance and sealing/filling failure, UPV, texture scanner, and flow rate were observed to assess crack performance.

All field test methods except surface crack evaluation were performed on selected cracks at each test section over two-year period (i.e., two winter seasons): before, after construction, and three times for the following years (i.e., spring and fall 2014, and spring 2015).

It should be noted that during the period between December 2013 and February 2014 Indiana recorded the 8th coldest winter along with the precipitation which was 125% of normal in Indiana. Freezing days (the maximum daily temperatures below 32°F) were 60 days. Consequently, an accelerated deterioration of crack and pavement conditions could be included in the evaluation.

4.3.1.1 Pavement Performance

4.3.1.1.1 IRI. Pavement profiles data were collected over time to evaluate functional performance of the test sections. The pavement profiles were analyzed with ProVAL (Version 3.40.0297) with 10 in. (250 mm) moving average to obtain IRIs. The analysis results are plotted in Figure 4.11.

X axis represents days before and after the construction. The first set of pavement profiles was collected a week before the construction of each section so it is shown as -7.Generally, IRI slightly decreased right after the construction, however all test sections showed gradual increase of IRIs over time.

Overall, the US-52 sections showed lower IRI values than that of the SR-43 sections did. In order to evaluate the effectiveness of sealing/filling, IRI changes between the crack sealing/filling and untreated sections were compared to each other. IRI changes were the difference between IRI collected over two years after the construction (i.e., the 5th data collection) and IRI collected right after the construction (i.e., the 2nd data collection). Table 4.2 summarizes the results. Shaded cells in the table represent the crack sealing/filling sections which outperformed the untreated section in terms of IRI changes. It is noteworthy that the statistical analysis to evaluate a significance of difference between the crack sealing/filling and untreated section could not be performed as IRI represents a ride quality over the entire length of each section so each section only had one IRI. In the table, the percentages of outperforming sections are also summarized.

The percentage of crack sealing/filling sections showed better performance than the untreated sections were 38% and 67% for the SR-43 and US-52 sections, respectively. Overall, 53% of the crack sealing/filling sections exhibited lower IRI than the untreated sections. In other words, 47% of the untreated sections showed poor performance than the crack sealing/filling

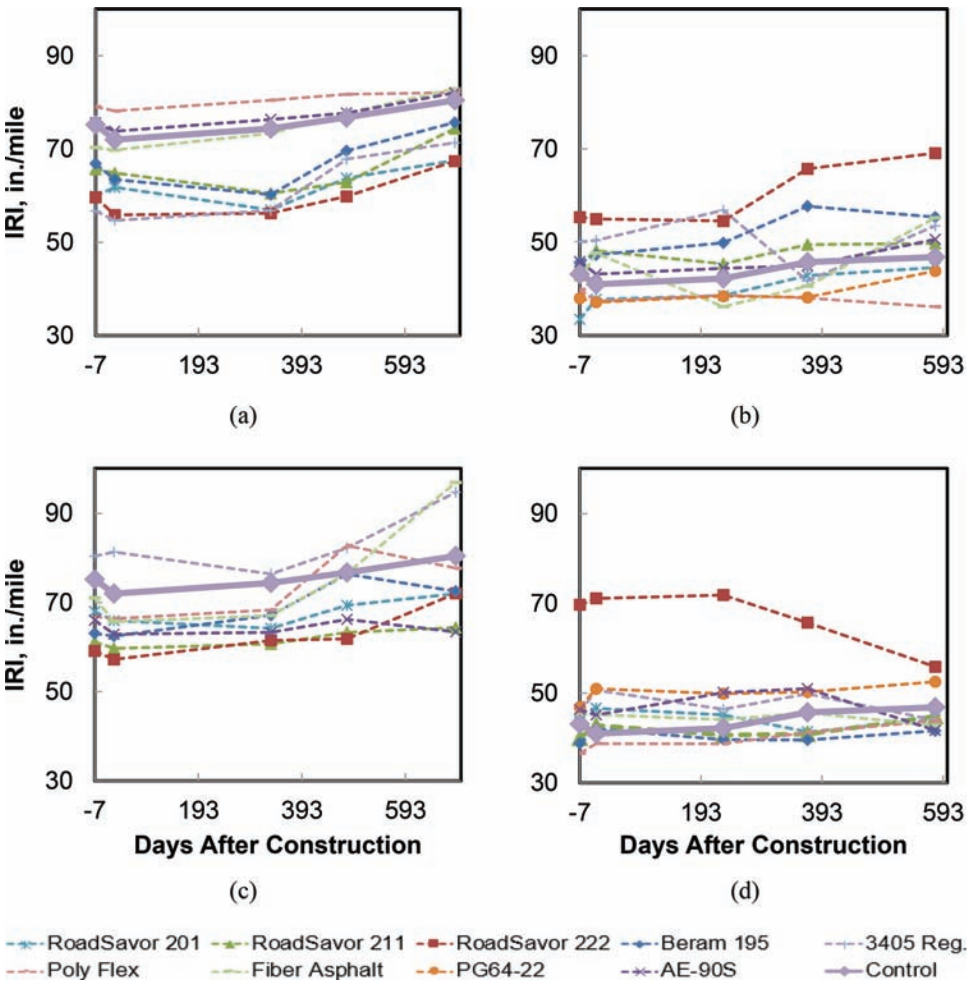


Figure 4.11 IRI: (a) SR-43 routed section; (b) US-52 routed section; (c) SR-43 non-routed section; (d) US-52 non-routed section.

TABLE 4.2
Comparison of IRI Changes between Crack Sealing/Filling and Untreated.

Crack Sealing/Filling Section vs. Untreated Section	SR-43 Routed	SR-43 Non-routed	US-52 Routed	US-52 Non-routed
AE-90S				
Poly Flex				
Fiber Asphalt				
RoadSavor 201				
RoadSavor 211				
RoadSavor 222				
Beram 195				
3405 Reg.				
PG 64-22	N/A	N/A		
Percentage of the crack sealing/filling sections outperforming the untreated sections (based on average change)	**3/8 (38%)**	**3/8 (38%)**	**4/9 (44%)**	**8/9 (89%)**
	6/16 (38%)		**12/18 (67%)**	
	18/34 (53%)			

NOTE: shaded cells represent the crack sealing/filling sections which outperformed the untreated sections.

sections did. Overall, the average IRI changes of the crack sealing/filling sections and untreated sections were 6.03 (STD: 7.99) and 7.16, respectively. Thus, the crack sealing/filling was not determined to be effective in terms of ride quality.

In order to evaluate the effectiveness of routing, the IRI changes between the routed and non-routed sections were compared to each other and the results are presented in Table 4.3. Shaded cells in the table represent the routed sections which outperformed the non-routed sections. The percentage of the routed sections in SR-43 and US-52 outperformed the non-routed sections were 50% and 22%, respectively. Overall, 35% of the routed sections outperformed the non-routed sections. In other words, 65% of the non-routed sections outperformed and showed lower IRI. The average IRI changes of the routed and non-routed sections were 7.96 (STD: 4.52) and 4.10 (STD: 10.0), respectively. Only 35% of the routed sections outperformed and the average IRI change of the routed sections was also higher than the non-routed sections. It can be concluded that the routing did not show any effectiveness in terms of IRI changes and may have caused increase of IRI.

TABLE 4.3
Comparison of IRI Changes between Routed and Non-routed Sections.

Routed Section vs. Non-routed Section	SR-43	US-52
AE-90S		
Poly Flex		
Fiber Asphalt		
RoadSavor 201		
RoadSavor 211		
RoadSavor 222		
Beram 195		
3405 Reg.		
PG 64-22	N/A	
Percentage of the routed sections outperforming the non-routed sections (based on average change)	**4/8 (50%)**	**2/9 (22%)**
	6/17 (35%)	

NOTE: shaded cells represent the routed sections which outperformed the non-routed sections.

4.3.1.1.2 Load Transfer Efficiency (LTE). LTE changes over time in the test sections are shown in Figure 4.12. LTE ranges from 50% to 80% and LTE increased right after the construction in most of the crack sealing/filling sections except five crack sealing/filling sections from US-52 routed sections: AE-90S, Poly Flex, PG 64-22, RoadSavor 211 and 222.

In general, LTE tends to decrease during winter (between 2nd and 3rd, and 4th and 5th data collections) and increases during summer (between 3rd and 4th data collection). Both the crack sealing/filling and the untreated sections show similar fluctuations over time.

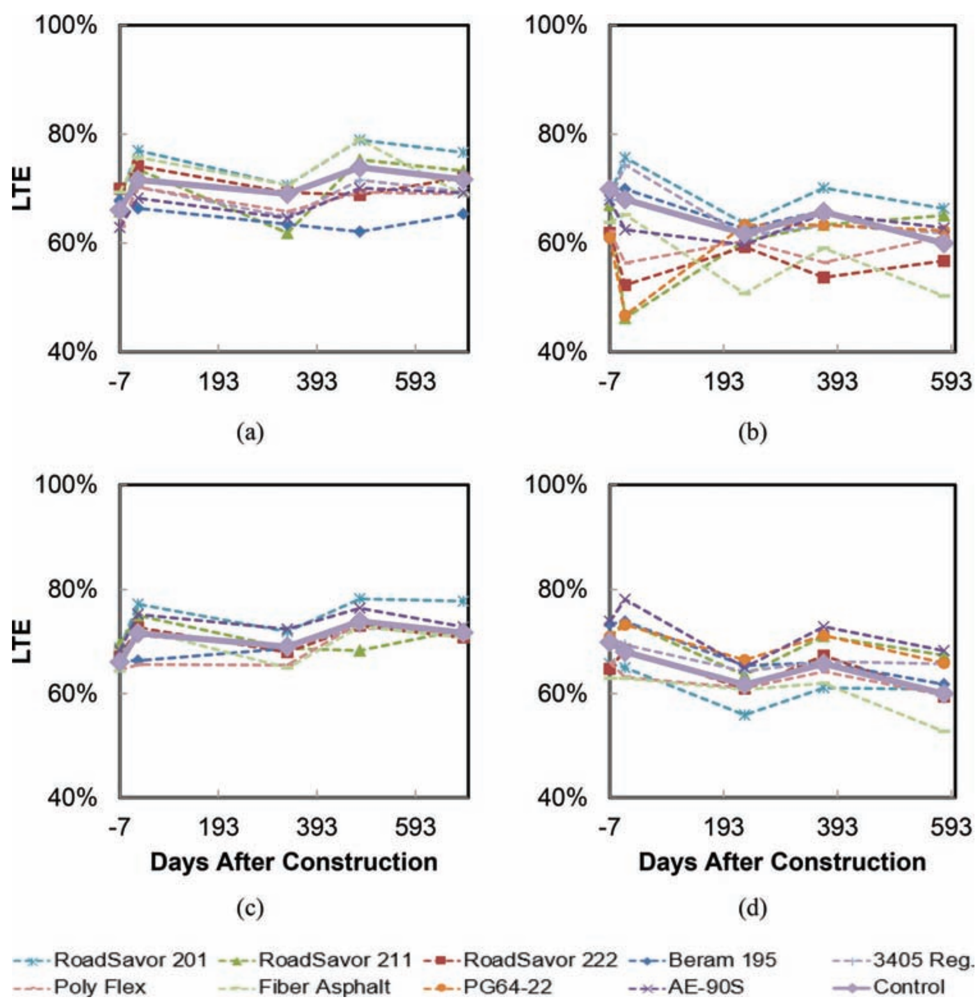


Figure 4.12 LTE: (a) SR-43 routed section; (b) US-52 routed section; (c) SR-43 non-routed section; (d) US-52 non-routed section.

The fluctuation could be due to spring thaw and traffic compaction after that.

To evaluate the crack sealing/filling effectiveness, the analysis method presented in Ch. 4.3.1.1.1 was applied and the results are shown in Table 4.4. In the table, shaded cells represent the crack sealing/filling sections outperformed the untreated section in terms of LTE. T-test was conducted to evaluate significance of the difference between the crack sealing/filling and untreated sections and numbers are shown in Table 4.4 are p-values. The threshold level were 10% (p-value: 0.1, study advisory board recommendation) and the same threshold level were applied to all other analysis presented in this chapter (Ch. 4.3.1). Bold numbers in the table are the statistically significant differences (p-value less than 0.1). Finally, the ones that were determined to be statistically significant and showed better performance than the untreated section were shown in shaded cells. In the table, the percentage of outperforming sections and the percentage of outperforming cells with statistical significance are also summarized.

The percentage of crack sealing/filling sections showed better performance than the untreated sections were 44% and 44% for the SR-43 and US-52 sections, respectively. Overall, 44% of the crack sealing/filling sections exhibited higher LTE than the untreated sections. When only the statistically significant sections (i.e., cells with bold numbers) were considered, the percentage of crack sealing/filling sections outperforming the untreated sections were 0% and 11% for the SR-43 and US-52 sections, respectively. Overall, the percentage of crack sealing/filling sections outperforming the untreated sections was 6%.Overall, the average LTE changes of the crack sealing/filling sections and untreated sections were -2% (STD: 7%) and -4% (STD: 3%), respectively. The results indicated that 44% of the crack sealing/filling section showed better performance than the untreated sections, however, the differences were determined to be statistically insignificant. The effectiveness of the crack/sealing was not observed in terms of LTE changes.

To evaluate the effectiveness of routing, the analysis method presented in Ch. 4.3.1.1.1 was applied and the results are shown in Table 4.5. T-test was conducted to evaluate significant differences between the routed and non-routed sections and p-values are presented in the table. The ones that the routed sections showed a better performance were shown in shaded cells and the bold numbers represent which were determined to be statistically significant. In the table, the percentage of outperforming sections and the percentage of outperforming cells with statistical significance are also summarized. The percentage of the routed sections in SR-43 and US-52 outperformed the non-routed sections were 38% and 56%, respectively. Overall, 47% of the routed sections outperformed the non-routed sections.

When only the statistically significant sections (i.e., cells with bold numbers) were considered, the percentage of outperforming routed sections were 13% and 44% for the SR-43 and US-52 sections, respectively. Overall, the percentage of outperforming routed sections was 29%.The average LTE changes of the

TABLE 4.4
Comparison of LTE Changes between Crack Sealing/Filling and Untreated Sections

Crack Sealing/Filling Section vs. Untreated Section	SR-43		US-52	
	Routed	Non-routed	Routed	Non-routed
AE-90S	0.901	0.627	0.319	0.809
Poly Flex	0.786	0.320	0.272	0.592
Fiber Asphalt	0.223	0.771	0.340	0.794
RoadSavor 201	0.929	0.924	0.856	0.676
RoadSavor 211	0.350	0.601	**0.011**	0.815
RoadSavor 222	0.658	0.680	0.223	0.888
Beram 195	0.905	0.136	0.805	0.678
3405 Reg.	0.856	0.875	0.614	0.554
PG 64-22	N/A	N/A	**0.015**	0.956
Percentage of the crack sealing/filling sections outperforming the untreated sections (based on average change)	**3/8 (38%)**	**4/8 (50%)**	**5/9 (56%)**	**3/9 (33%)**
	7/16 (44%)		**8/18 (44%)**	
	15/34 (44%)			
Percentage of the crack sealing/filling sections outperforming the untreated sections (based on p-value < 0.1)	**0/8 (0%)**	**0/8 (0%)**	**2/9 (22%)**	**0/9 (0%)**
	0/16 (0%)		**2/18 (11%)**	
	2/34 (6%)			

NOTE: Shaded cells represent the crack sealing/filling sections which outperformed the untreated sections.
Numbers are p-values; bold numbers indicate statistical significance (less than 0.1).

TABLE 4.5
Comparison of LTE Changes between Routed and Non-routed Sections.

Routed Section vs. Non-routed Section	SR-43	US-52
AE-90S	0.932	**0.093**
Poly Flex	0.534	0.187
Fiber Asphalt	0.153	0.239
RoadSavor 201	**0.022**	0.523
RoadSavor 211	0.767	0.157
RoadSavor 222	0.414	**0.001**
Beram 195	**0.096**	**0.057**
3405 Reg.	0.141	0.274
PG 64-22	N/A	**0.094**
Percentage of the routed sections outperforming the non-routed sections (based on average change)	**3/8 (38%)**	**5/9 (56%)**
	8/17 (47%)	
Percentage of the routed sections outperforming the non-routed sections (based on average change)	**1/8 (13%)**	**4/9 (44%)**
	5/17 (29%)	

NOTE: Shaded cells represent the routed sections which outperformed the non-routed sections.
Numbers are p-values; bold numbers indicate statistical significance (less than 0.1).

routed and non-routed sections were -1% (STD: 9%) and -4% (STD: 5%), respectively. It was interesting to note that the decrease of LTE in non-routed sections was 3pp more than the routed sections, however only 29% of the routed sections showed better performance which was statistically significant. The effectiveness of routing in terms of LTE could not be found.

4.3.1.1.3 Asphalt Modulus. Asphalt modulus is another widely used structural performance index for pavement performance and results are shown in Figure 4.13. Asphalt modulus increased after the construction in the SR-43 sections, however, the decrease was observed in the US-52 sections. Asphalt modulus fluctuated between seasons in a similar way to the LTE fluctuation did. Unlike LTE, modulus, in general, gradually decreased over time. From the last measurements, all other crack sealing/filling sections showed higher modulus than that of untreated sections in both test roads.

To evaluate the crack sealing/filling effectiveness, the analysis method presented in Ch. 4.3.1.1.1 and the statistical analysis method presented in Ch. 4.3.1.1.2 were applied and the results are shown in Table 4.6. The percentage of crack sealing/filling sections showed better performance than the crack sealing/filling sections were 25% and 22% for the SR-43 and US-52 sections, respectively. Overall, 24% of the crack sealing/filling sections exhibited higher asphalt modulus than the untreated sections. When only the statistically significant sections (i.e., cells with bold numbers) were considered, the percentage of outperforming crack sealing/filling sections were 13% and 7% for the SR-43 and US-52 sections, respectively. Overall, the percentage of outperforming crack sealing/filling sections was 9%. Overall, the average asphalt modulus changes of the crack sealing/filling section and untreated sections were -64.0 ksi (STD: 56.9 ksi) and -103.0 ksi, respectively. The average changes of asphalt modulus of the crack sealing/filling sections were lower than the crack sealing/filling sections, however the percentage of outperforming sections was only 9%. Overall, the effectiveness of sealing/filling was minimal in terms of asphalt modulus changes.

To evaluate the routing effectiveness, the analysis method presented in Ch. 4.3.1.1.1 and the statistical analysis method presented in Ch. 4.3.1.1.2 were applied and the results are shown in Table 4.7. The percentage of the routed sections in SR-43 and US-52 outperformed the non-routed sections were 13% and 22%, respectively. Overall, 18% of the routed sections outperformed. When only the statistically significant sections (i.e., cells with bold numbers) were considered, the percentage of outperforming routed sections were 13% and 12% for the SR-43 and US-52 sections, respectively. Overall, the percentage of outperforming routed sections was 11%. The average IRI changes of the routed and non-routed sections were -58.2 ksi (STD: 65.6 ksi) and -69.8 ksi (STD: 45.8 ksi), respectively. The asphalt modulus decreased less in the routed sections, however the difference was not determined to be significant as only 11% of the crack sealing/filling sections showed better performance. The effectiveness of routing was not shown in terms of asphalt modulus changes.

4.3.1.1.4 Surface Crack Evaluation. Two surface crack surveys were conducted, before and two years after the construction. Cracks were categorized in terms of distress type: longitudinal crack, transverse crack, and fatigue crack. An example of survey image is shown in Figure 4.14. For the analysis, the length-based measurement was used in order to add up the

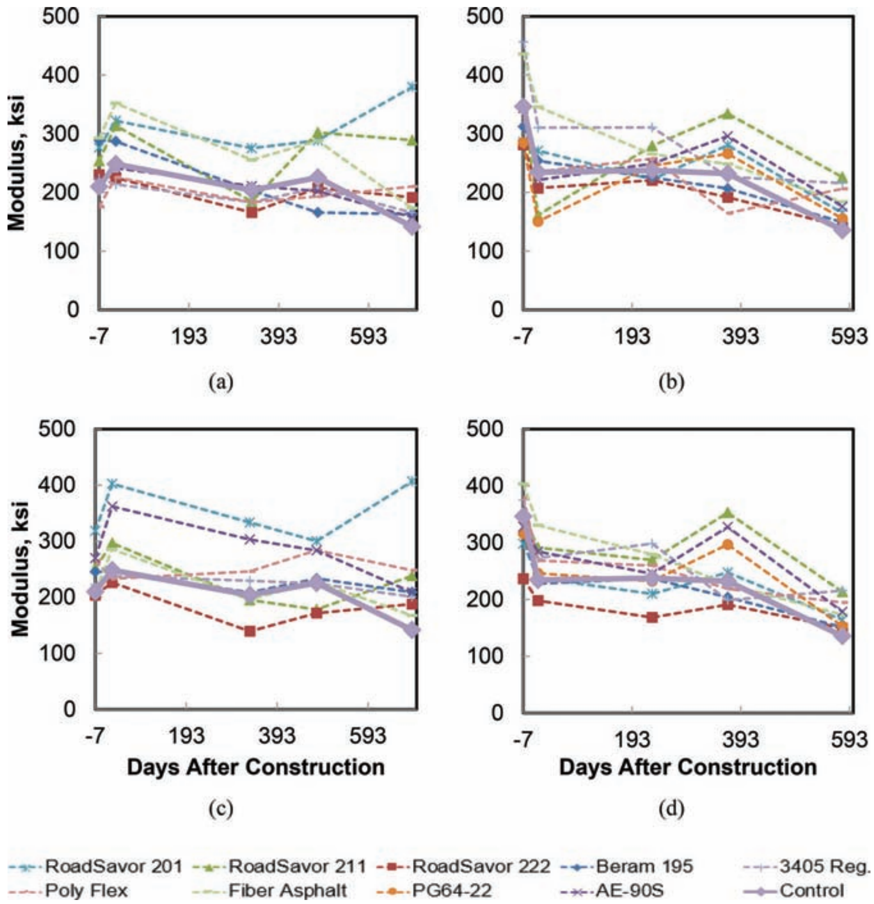


Figure 4.13 Modulus: (a) SR-43 routed section; (b) US-52 routed section; (c) SR-43 non-routed section; (d) US-52 non-routed section.

TABLE 4.6
Comparison of Asphalt Modulus Changes between Crack Sealing/Filling and Untreated Sections.

Crack Sealing/Filling Section vs. Untreated Section	SR-43		US-52	
	Routed	Non-routed	Routed	Non-routed
AE-90S	0.684	0.424	0.127	0.841
Poly Flex	0.102	0.105	0.358	0.605
Fiber Asphalt	0.187	0.817	0.107	0.547
RoadSavor 201	**0.036**	0.108	0.838	0.556
RoadSavor 211	**0.050**	0.362	**0.003**	0.502
RoadSavor 222	0.168	0.203	0.632	0.129
Beram 195	0.940	**0.074**	0.896	0.406
3405 Reg.	0.259	0.209	0.915	0.324
PG 64-22	N/A	N/A	0.915	**0.007**
Percentage of the crack sealing/filling sections outperforming the untreated sections (based on average change)	**3/8 (38%)**	**1/8 (13%)**	**2/9 (22%)**	**2/9 (22%)**
	4/16 (25%)		**4/18 (22%)**	
	8/34 (24%)			
Percentage of the crack sealing/filling sections outperforming the untreated sections (based on p-value < 0.1)	**2/8 (25%)**	**0/8 (0%)**	**1/9 (11%)**	**0/9 (0%)**
	2/16 (13%)		**1/18 (7%)**	
	3/34 (9%)			

NOTE: shaded cells represent the crack sealing/filling sections which outperformed the untreated sections.

Numbers are p-values; bold numbers indicate statistical significance (less than 0.1).

TABLE 4.7
Comparison of Asphalt Modulus Changes between Routed and Non-routed Sections.

Routed Section vs. Non-routed Section	SR-43	US-52
AE-90S	0.376	0.289
Poly Flex	0.846	0.237
Fiber Asphalt	0.708	0.584
RoadSavor 201	**0.025**	0.191
RoadSavor 211	0.642	0.542
RoadSavor 222	0.630	0.711
Beram 195	0.957	0.107
3405 Reg.	0.260	0.635
PG 64-22	N/A	**0.098**
Percentage of the routed sections outperforming the non-routed sections (based on average change)	**1/8 (13%)**	**2/9 (22%)**
	3/17 (18%)	
Percentage of the routed sections outperforming the non-routed sections (based on average change)	**1/8 (13%)**	**1/9 (11%)**
	2/17 (12%)	

NOTE: Shaded cells represent the routed sections which outperformed the non-routed sections.
Numbers are p-values; bold numbers indicate statistical significance (less than 0.1).

extents of different types of cracks and Figure 4.15 presents the average crack length change per 100 ft of the test sections over time. In case of the fatigue crack, the longitudinal length of each fatigue crack area was measured.

In general, the extents of cracks were similar between crack sealing/filling sections in SR-43 and US-52, however the untreated sections showed a different results. The untreated section in US-52 showed a much higher occurrence of surface crack than the SR-43 untreated section. Furthermore, the SR-43 untreated section showed relatively lower extents of crack than other crack sealing/filling sections in SR-43.

To evaluate the crack sealing/filling effectiveness, the analysis method presented in Ch. 4.3.1.1.1 was applied and the results are shown in Table 4.8 summarizes the individual section comparison results to their untreated section. The statistical analysis could not be performed as only average crack length was available for each section. The percentage of crack sealing/filling sections showed better performance than the crack sealing/ filling sections were 25% and 100% for the SR-43 and US-52 sections, respectively. Overall, 65% of the crack sealing/filling sections exhibited less average crack length than the untreated sections. Overall, the average crack length changes of the crack sealing/filling

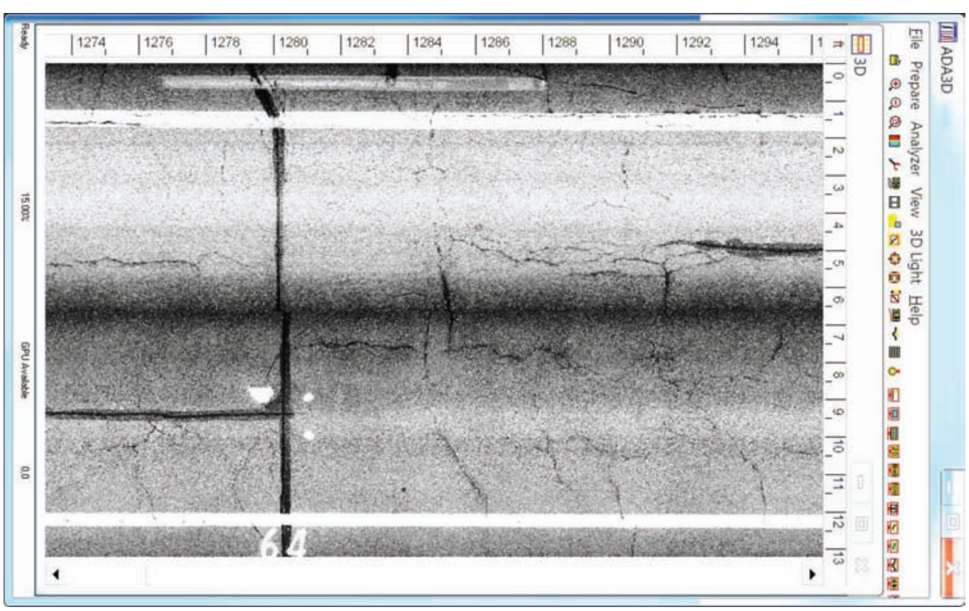


Figure 4.14 Example of survey image for surface crack analysis.

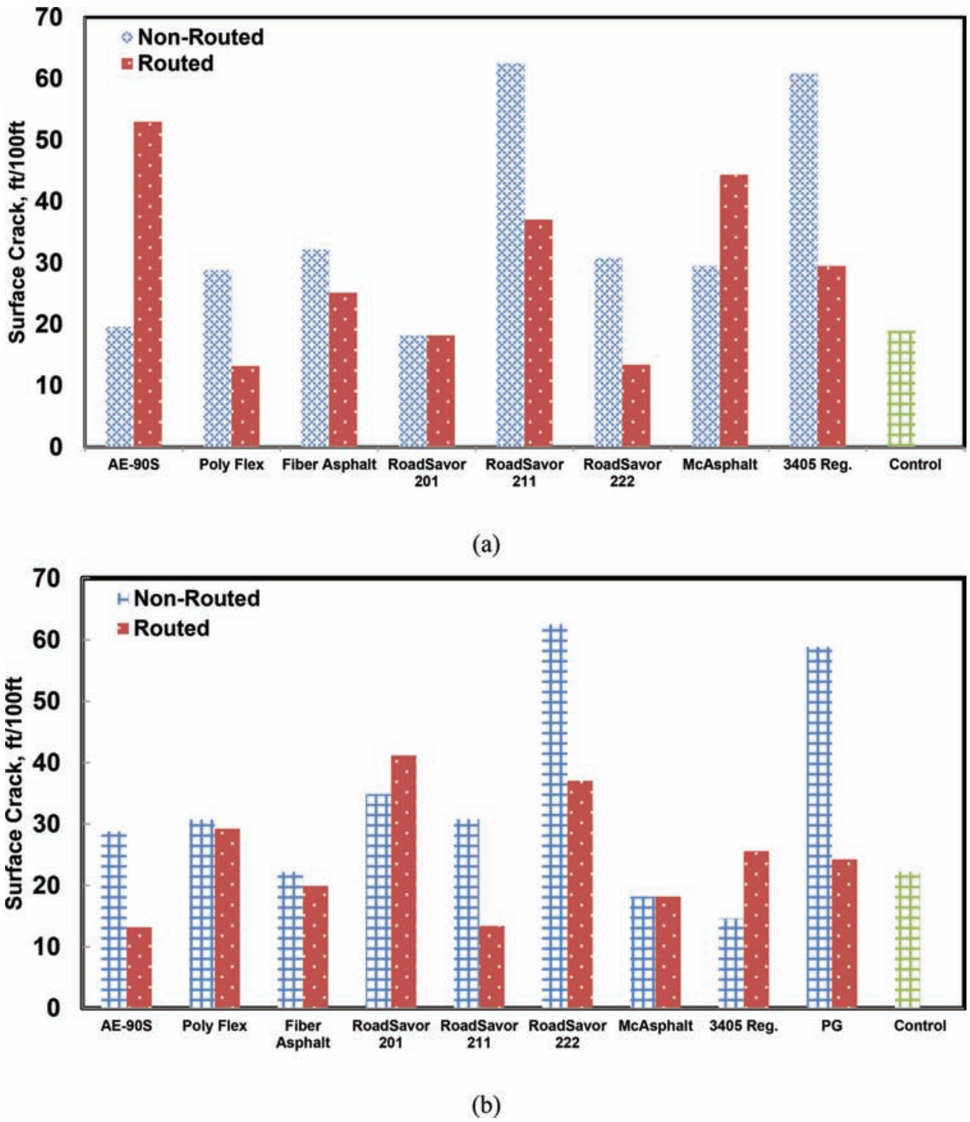


Figure 4.15 Surface crack: (a) SR-43 section; (b) US-52 section.

sections and untreated sections were 30.6 ft/100ft (STD: 14.5 ft/100ft) and 46.7 ft/100ft, respectively. It should be noted that there was a large difference of average crack length between the untreated sections in US-52 and SR-43, and the SR-43 untreated section showed a lower average crack length even compared to that of other crack sealing/filling sections in SR-43. The average crack length of crack sealing/filling sections in both SR-43 and US-52 were less than that of the US-52 untreated section and the sealing/filling was concluded to have positive effect on preventing surface crack distress occurrence in the pavement.

To evaluate the routing effectiveness, the analysis method presented in Ch. 4.3.1.1.1 was applied and the results are shown in Table 4.9. The percentage of the routed sections in SR-43 and US-52 outperformed the non-routed sections were 50% and 33%, respectively. Overall, 47% of the routed sections outperformed. Overall, the average crack length changes of the routed sections and non-routed sections were 26.8 ft/100ft (STD: 11.8 ft/100ft) and 34.4 ft/100ft (STD: 15.9 ft/100ft), respectively. The percentage of the outperforming routed sections is 47% and the average crack length of the routed and non-routed sections were also similar to each other. The effectiveness of routing in terms of surface crack evaluation was not found.

4.3.1.2 Crack Performance

4.3.1.2.1 Adhesive/Cohesive/Spalling (ACS) Failure. Visual inspection was conducted on each crack image collected from the test sections. There were three types of failures observed, adhesive failure, cohesive failure, and spalling (or material loss), and example of each failure type is shown in Figure 4.16. The figure shows that overall and close-up pictures of cracks displaying each type of failures. It was not easy to define the

TABLE 4.8
Comparison of Surface Crack Changes between Crack Sealing/Filling and Untreated Sections.

Crack Sealing/Filling Section vs. Untreated Section	SR-43		US-52	
	Routed	Non-routed	Routed	Non-routed
AE-90S				
Poly Flex				
Fiber Asphalt				
RoadSavor 201				
RoadSavor 211				
RoadSavor 222				
Beram 195				
3405 Reg.				
PG 64-22	N/A	N/A		
Percentage of the crack sealing/filling sections outperforming the untreated sections (based on average change)	3/8 (38%)	1/8 (13%)	9/9 (100%)	9/9 (100%)
	4/16 (25%)		18/18 (100%)	
	22/34 (65%)			

NOTE: Shaded cells represent the crack sealing/filling sections which outperformed the untreated sections.

TABLE 4.9
Comparison of Surface Crack Changes between Routed and Non-routed Sections

Routed Section vs. Non-routed Section	SR-43	US-52
AE-90S		
Poly Flex		
Fiber Asphalt		
RoadSavor 201		
RoadSavor 211		
RoadSavor 222		
Beram 195		
3405 Reg.		
PG 64-22	N/A	
Percentage of the routed sections outperforming the non-routed sections (based on average change)	4/8 (50%)	3/9 (33%)
	8/17 (47%)	

NOTE: Shaded cells represent the routed sections which outperformed the non-routed sections.

failure types in most of cases using only images. All failure lengths, regardless of the failure types, were added and the percentages of failure were calculated. The results are shown in Figure 4.17. No failure was observed right after the construction and failure began to occur after first winter season.

Overall, the US-43 sections showed more failure than the US-52 sections did and the non-routed sections exhibited earlier occurrence and higher rate of ACS failure. With the ACS failure data, effectiveness of sealing/filling could not be analyzed as untreated section was not available for comparison. Thus, only the routing effectiveness was conducted using the analysis method presented in Ch. 4.3.1.1.1 and the statistical analysis method presented in Ch. 4.3.1.1.2 were applied and the results are shown in Table 4.10. The percentage of the routed sections in SR-43 and US-52 outperformed the non-routed sections were 88% and 100%, respectively. Overall, 94% of the routed sections outperformed the non-routed sections. When only the statistically significant sections (i.e., cells with bold numbers) were considered, the percentages of routed sections outperforming the non-routed sections were 63% and 67% for the SR-43 and US-52 sections, respectively. Overall, the percentage of routed sections outperforming the non-routed sections was 65%. The ACS failure of the routed sections ranged between 9% and 70% and the average was 35%. The asphalt modulus changes of the non-routed sections ranged between 15% and 99% and the average was 81%. Overall, 65% of the routed sections showed less ACS failures than the non-routed sections and the average of ACS failure was 81% which was 46 pp higher than that of the non-routed sections. It can be concluded that routing is effective in minimizing ACS failures.

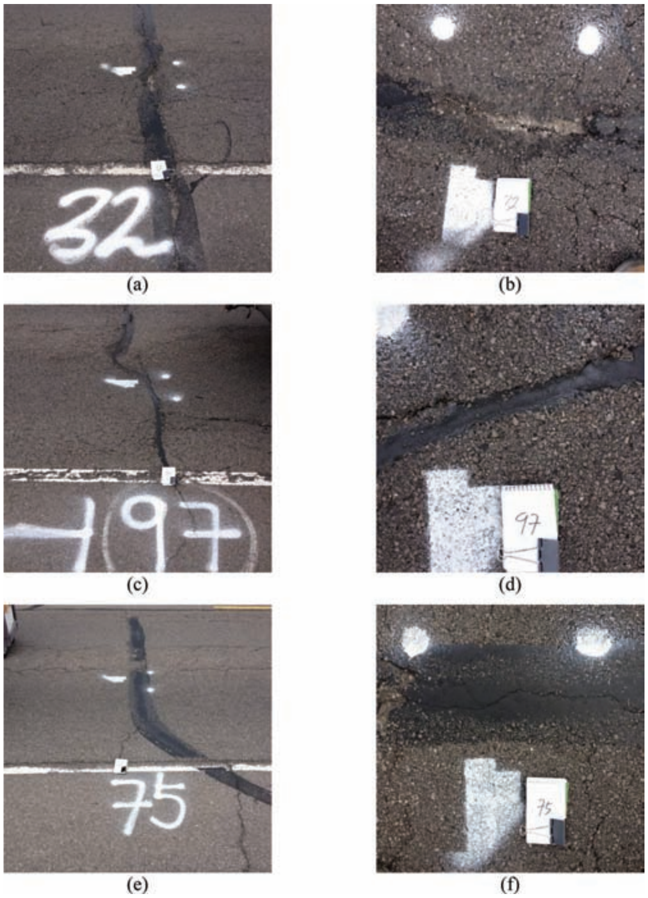


Figure 4.16 Sealing/filling failure type: (a) and (b) spalling; (c) and (d) adhesive failure; (e) and (f) cohesive failure.

4.3.1.2.2 Ultrasonic Pulse Velocity. UPV test was conducted on the crack area and the travel time between transducer and receiver was measured in order to understand mechanical conditions of cracks with crack sealing/filling material. The ultrasonic pulse travel time increase with increasing extent of discontinuity conditions in medium. The UPVs over time with different treatment material and types are shown in Figure 4.18. It should be noted that all measurements were calibrated for 70°F. The plot showed both increase and decrease in travel time among the crack sealing/filling sections right after the construction but overall the changes were not significant. The travel time was greater in the untreated sections.

Overall, the performance of the untreated sections became worse over time and difference between the crack sealing/filling sections and the untreated sections were significant after two years. The performance of the crack sealing/filling sections also started to deteriorate after 4th data collection and the trend also agreed with the findings from the crack sealing/filling failure. To evaluate the crack sealing/filling effectiveness, the analysis method presented in Ch. 4.3.1.1.1 and the statistical analysis method presented in Ch. 4.3.1.1.2 were applied and the results are shown in Table 4.11. The percentages of crack sealing/filling sections showed better performance than the untreated sections were 88% and 100% for the SR-43 and US-52 sections, respectively. Overall, 94% of the crack sealing/filling sections exhibited lower UPV than the untreated sections. When only the statistically significant sections (i.e., cells with bold numbers) were considered, the percentage of crack sealing/filling sections outperforming the untreated sections were 50% and 44% for the SR-43 and US-52 sections, respectively. Overall, the percentage of crack sealing/filling sections outperforming the untreated sections was 47%. Overall, the average UPV changes of the crack sealing/filling sections and untreated sections were 15.8 μs (STD: 53.1 μs) and 52.2 μs, respectively. The UPV changes of the untreated sections were higher and 94% of the crack sealing/filling sections performed better than the untreated sections. The average change of UPV on crack in the crack sealing/filling sections was 36.4 μs less than the untreated sections even though the statistically significant percentage of outperforming crack sealing/filling sections decreased to 47%. Thus, the crack sealing/filling was concluded to be effective in maintaining crack integrity.

To evaluate the routing effectiveness, the analysis method presented in Ch. 4.3.1.1.1 and the statistical analysis method presented in Ch. 4.3.1.1.2 were applied and the results are shown in Table 4.12. The percentage of the routed sections in SR-43 and US-52 outperformed the non-routed sections were 63% and 78%, respectively. Overall, 71% of the routed sections outperformed. When only the statistically significant sections (i.e., cells with bold numbers) were considered, the percentage of outperforming routed sections were 13% and 33% for the SR-43 and US-52 sections, respectively. Overall, the percentage of outperforming routed sections was 24%. Overall, the average UPV changes of the routed sections and non-routed sections were 24.8 μs (STD: 33.7 μs) and 19.8 μs (STD: 38.37 μs), respectively. The UPV changes of the routed sections were greater than the non-routed sections and the percentage of routed sections outperforming the non-routed sections was only 24%. The routing was not determined to be effective in terms of crack integrity.

4.3.1.2.3 Texture Scanner. The reservoir shape changes were measured using the texture scanner and the reservoir void volume was calculated to understand the seasonal crack contraction and expansion. The example texture scanner images are shown in Figure 4.19. The reservoir volumes are shown in Figure 4.20. The figure showed that the reservoir volume decreased right after the construction as the reservoir or crack was filled with materials. Overall, it can be observed that volume increased during winter (2nd and 3rd data collection) as the pavement contracts and decreases during summer (3rd and 4th data collection). The untreated sections showed higher volumes but a few routed sections showed higher volume than that of the untreated sections. It should be noted that the volume was measured form the surface of the material and materials placed on the routed crack sank over time.

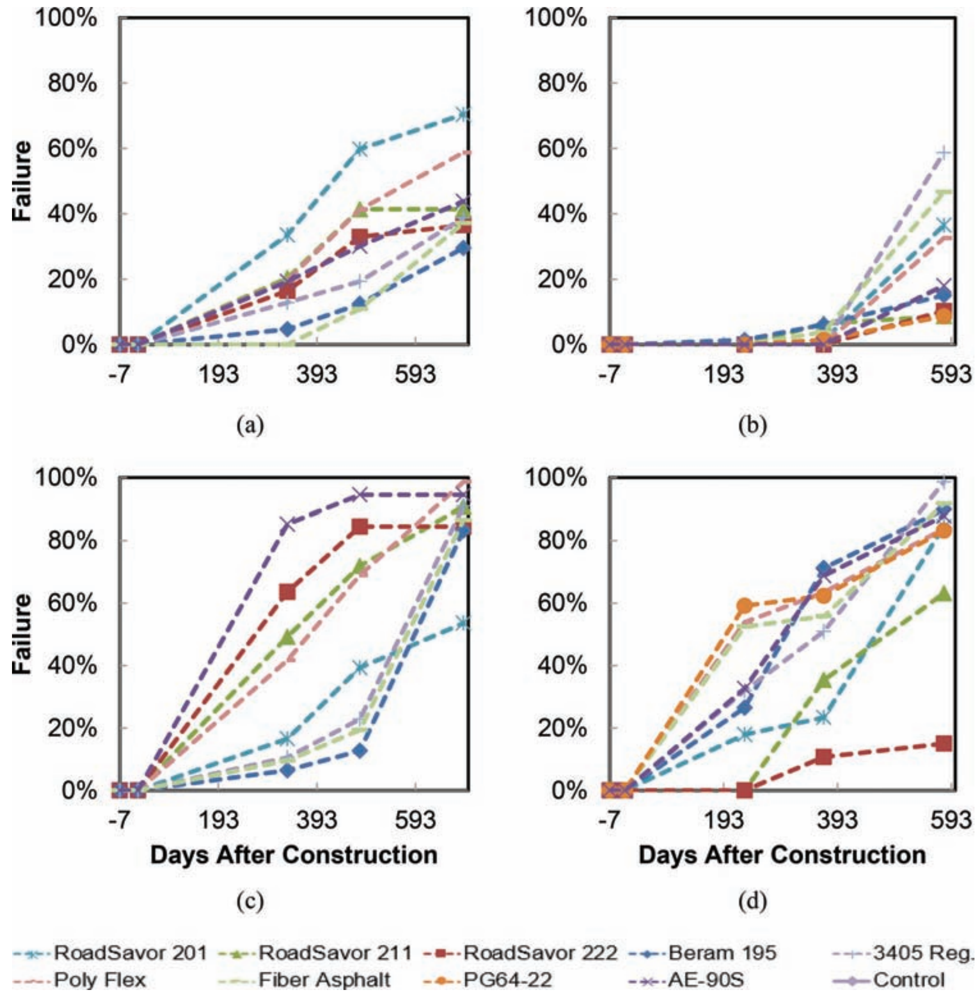


Figure 4.17 Sealing/filling failure: (a) SR-43 routed section; (b) US-52 routed section; (c) SR-43 non-routed section; (d) US-52 non-routed section.

TABLE 4.10
Comparison of Sealing/Filling Failure Changes between Routed and Non-routed Sections

Routed Section vs. Non-routed Section	SR-43	US-52
AE-90S	**0.084**	**0.020**
Poly Flex	**0.016**	**0.065**
Fiber Asphalt	0.712	**0.053**
RoadSavor 201	**0.000**	0.221
RoadSavor 211	**0.026**	**0.095**
RoadSavor 222	**0.021**	**0.000**
Beram 195	**0.004**	0.348
3405 Reg.	0.436	0.358
PG 64-22	N/A	**0.000**
Percentage of the routed sections outperforming the non-routed sections (based on average change)	**7/8 (88%)**	**9/9 (100%)**
	16/17 (94%)	
Percentage of the routed sections outperforming the non-routed sections (based on p-value < 0.1)	**5/8 (63%)**	**6/9 (67%)**
	11/17 (65%)	

NOTE: Shaded cells represent the routed sections which outperformed the non-routed sections.
Numbers are p-values; bold numbers indicate statistical significance (less than 0.1).

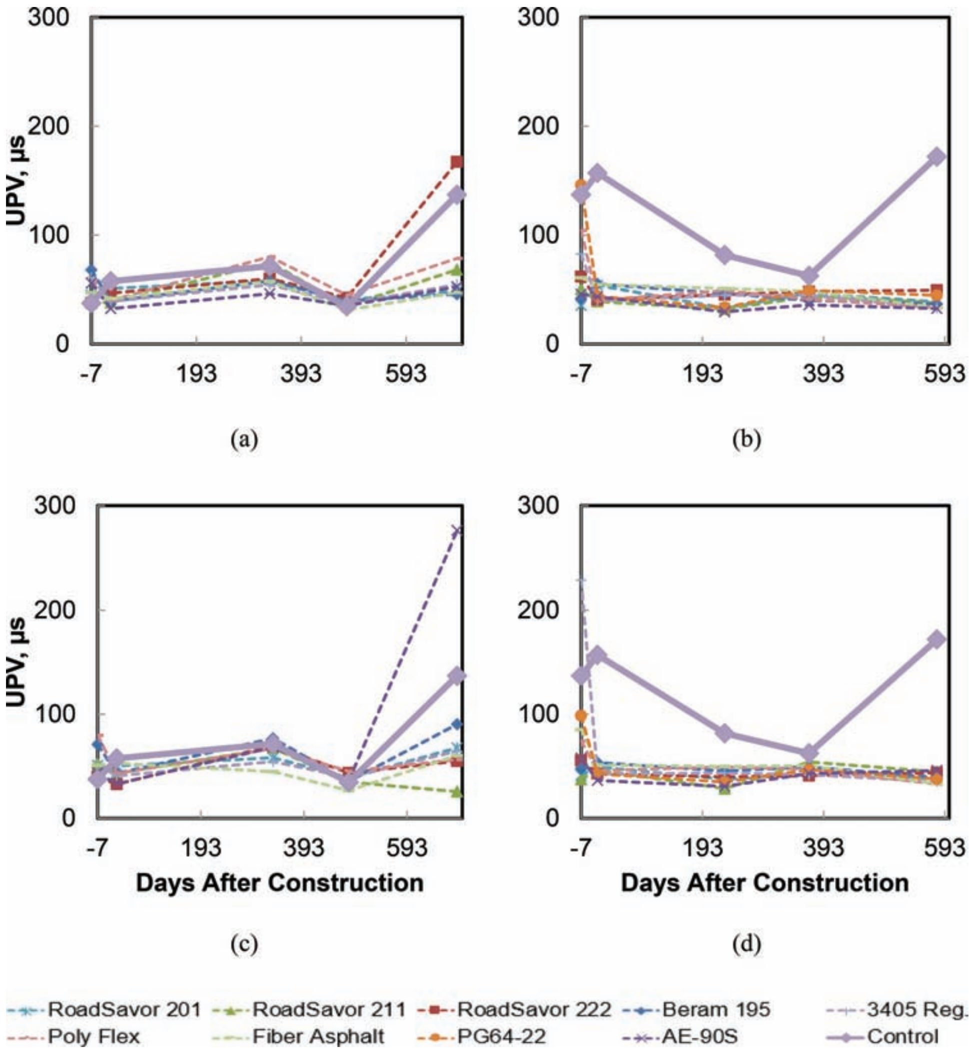


Figure 4.18 UPV on crack: (a) SR-43 routed section; (b) US-52 routed section; (c) SR-43 non-routed section; (d) US-52 non-routed section.

To evaluate the crack sealing/filling effectiveness, the analysis method presented in Ch. 4.3.1.1.1 and the statistical analysis method presented in Ch. 4.3.1.1.2 were applied and the results are shown in Table 4.13. The percentages of crack sealing/filling sections outperforming the untreated sections were 88% and 89% for the SR-43 and US-52 sections, respectively. Overall, 88% of the crack sealing/filling sections exhibited less volume than the untreated sections. When only the statistically significant sections (i.e., cells with bold numbers) were considered, the percentage of crack sealing/filling sections outperforming the untreated sections were 56% and 67% for the SR-43 and US-52 sections, respectively. The percentage of crack sealing/filling sections outperforming the untreated sections was 62%. Overall, the average volume changes of the crack sealing/filling sections and untreated sections were 0.24 in^3 (STD: 0.30 in^3) and 0.73 in^3, respectively. Overall, the percentage of crack sealing/filling sections outperforming the untreated sections was 62%. As a result, it could be concluded that the sealing/filling was effective in resisting sealant and filler deformations due to the seasonal crack movement.

To evaluate the routing effectiveness, the analysis method presented in Ch. 4.3.1.1.1 and the statistical analysis method presented in Ch. 4.3.1.1.2 were applied and the results are shown in Table 4.14. The percentage of the routed sections in SR-43 and US-52 outperformed the non-routed sections were 50% and 11%, respectively. Overall, 29% of the routed sections outperformed. When only the statistically significant sections (i.e., cells with bold numbers) were considered, the percentage of outperforming routed sections were 13% and 11% for the SR-43 and US-52 sections, respectively. Overall, the percentage of outperforming routed sections was 12%. The average volume changes of the routed and non-routed sections were 0.99 in^3 (STD: 1.05 in^3) and 0.09 in^3 (STD: 0.12 in^3), respectively. Only 12% of the routed sections showed a better performance than the non-routed sections, and the routed sections showed higher average volume changes. It could be due to the change of material shape in the routed cracks may have attributed to larger void volume of the routed cracks than that of non-routed cracks. The routing was not determined to be effective in terms of material deformation.

TABLE 4.11
Comparison of UPV on Crack Changes between Crack Sealing/Filling and Untreated Sections.

Crack Sealing/Filling Section vs. Untreated Section	SR-43		US-52	
	Routed	Non-routed	Routed	Non-routed
AE-90S	0.452	0.285	**0.095**	0.400
Poly Flex	0.920	**0.008**	**0.078**	0.460
Fiber Asphalt	**0.002**	**0.007**	**0.056**	**0.055**
RoadSavor 201	**0.027**	**0.040**	**0.047**	**0.092**
RoadSavor 211	0.512	**0.002**	0.148	0.169
RoadSavor 222	0.782	0.306	0.143	0.251
Beram 195	**0.046**	0.380	**0.071**	**0.086**
3405 Reg.	0.210	**0.020**	0.135	0.170
PG 64-22	N/A	N/A	0.893	0.246
Percentage of the crack sealing/filling sections outperforming the untreated sections (based on average change)	**7/8 (88%)**	**7/8 (88%)**	**9/9 (100%)**	**9/9 (100%)**
	14/16 (88%)		**18/18 (100%)**	
	32/34 (94%)			
Percentage of the crack sealing/filling sections outperforming the untreated sections (based on p-value < 0.1)	**3/8 (38%)**	**5/8 (63%)**	**5/9 (56%)**	**3/9 (33%)**
	8/16 (50%)		**8/18 (44%)**	
	16/34 (47%)			

NOTE: Shaded cells represent the crack sealing/filling sections which outperformed the untreated sections.
Numbers are p-values; bold numbers indicate statistical significance (less than 0.1).

TABLE 4.12
Comparison of UPV on Crack Changes between Routed and Non-routed Sections.

Routed Section vs. Non-routed Section	SR-43	US-52
AE-90S	0.254	0.234
Poly Flex	**0.056**	0.657
Fiber Asphalt	**0.033**	**0.020**
RoadSavor 201	0.290	**0.029**
RoadSavor 211	0.116	0.304
RoadSavor 222	0.232	0.343
Beram 195	0.194	0.213
3405 Reg.	0.404	**0.008**
PG 64-22	N/A	0.477
Percentage of the routed sections outperforming the non-routed sections (based on average change)	**5/8 (63%)**	**7/9 (78%)**
	12/17 (71%)	
Percentage of the routed sections outperforming the non-routed sections (based on p-value < 0.1)	**1/8 (13%)**	**3/9 (33%)**
	4/17 (24%)	

NOTE: Shaded cells represent the routed sections which outperformed the non-routed sections.
Numbers are p-values; bold numbers indicate statistical significance (less than 0.1).

4.3.1.2.4 Permeability. Permeability was measured on both crack and non-crack area. Then the ratio between crack and non-crack area was calculated, as shown in Figure 4.22. The closer the ratio is to 1, the more the condition of crack area resembles that of non-crack area. In other words, a lower ratio represents a better performance. It should be noted that materials applied into routed crack sank over time, as shown in Figure 4.21, and the material shape greatly affected the test results. On routed cracks, water leaked due to void area caused by material shape change. Thus, permeability data were not included in the analysis.

4.3.2 Material Performance

A relative performance of sealing/filling products was evaluated by application type (sealing vs. filling) for each test method to come up with material performance ranking based on the field test results. In order to compare the performances of each sealant and filler, each sealant and filler was sorted and statistical analysis was conducted by application type (i.e., sealing and filling) to assess if the difference was also statistically significant. The difference between

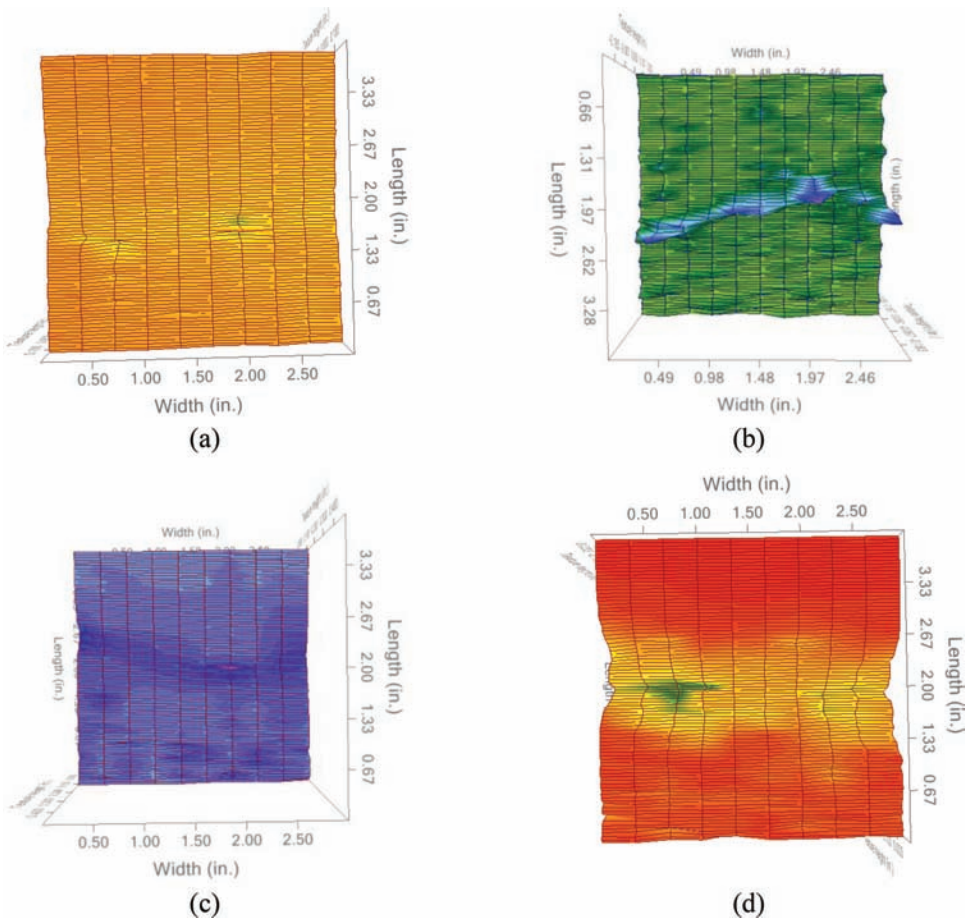


Figure 4.19 Texture scanner images: (a) narrow crack; (b) wide crack; (c) filled crack (2070 Activity); (d) sealed crack after routing (2090 Activity).

data collected two years after the construction (i.e., the 5th data collection) and data collected right after the construction (i.e., the 2nd data collection) were used for the analysis.

The relative material performance ranking for crack filling and crack sealing application are shown in Table 4.15 and Table 4.16. In the tables, the best and worst performing sealant and filler were shown in shaded cells for each test method. It should be noted that if the same ranking are assigned for more than one sealant or filler, it indicated that the performance difference was not statistically significant.

ACS failure directly represents the performance of crack sealing/filling and the most widely used evaluation method. To evaluate the performance of sealant and filler in terms of ACS, failure is represented by the results of other test methods, linear regression analysis was conducted by application type (i.e., sealing and filling). The difference between data collected two years after the construction (i.e., the 5th data collection) and data collected right after the construction (i.e., the 2nd data collection) were used for the analysis. The results are shown in Table 4.17.

The parameter estimates represent the slope of the best fitted line and the sign indicates either positive or negative relationship. For instance, the parameter estimate for LTE is negative, thus the higher the LTE becomes, the less crack sealing/filling occurs. To evaluate the significance of relationship, p-value was observed for each test method. The threshold for all statistical analysis was set to be 10% (p-value: 0.1), as noted in Ch. 4.3.1.1.2. As a result, there was no statistically significant between test methods. In terms of ACS failure, PG and RoadSavor 222 showed the best performances for crack filling and sealing applications, respectively. The test results indicated that ASTM 6690 Type II crack sealants performed relatively well in terms of pavement and crack performances.

The correlations between the ACS failure and the other tests were overall very poor with high P-values, which concluded that material performances (ACS failure) do not significantly influence the pavement and crack performance in two years. On the other hand, AE-90S, which is primarily used for the filling application in INDOT, did not show good performance. Thus the AE-90S use on crack filling application (2070 Activity) is no longer recommended. The test

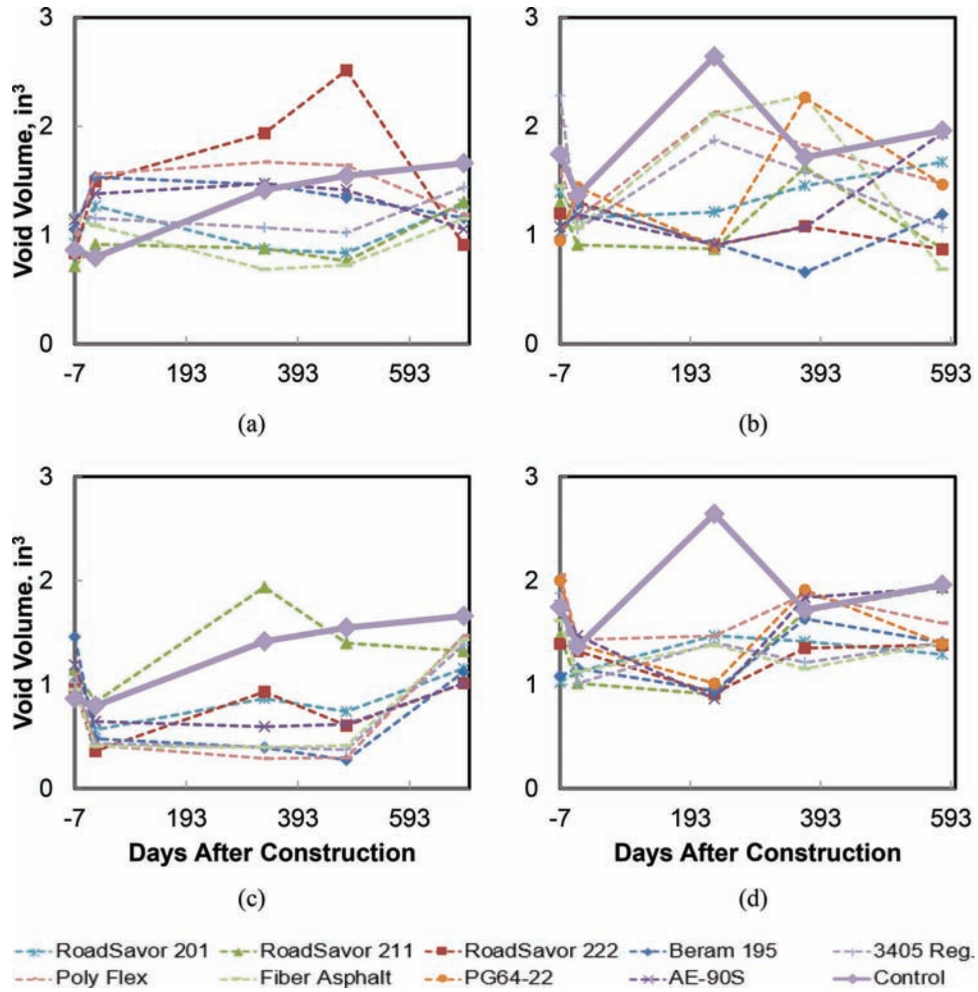


Figure 4.20 Modulus: (a) SR-43 routed section; (b) US-52 routed section; (c) SR-43 non-routed section; (d) US-52 non-routed section.

results showed that there are some better performed sealants and fillers than AE-90S. AE-90S costs about 65% of the sealants. However, considering the residue of emulsion (e.g., 65%), the sealants have competitive price. Therefore, replacing AE-90S with the other crack sealants or filler for the filling application (2070 Activity) should be considered.

4.3.3 Evaluation of Sealant Grade Testing

Knowing the property of sealant and filler and how the property is related to the field performance is critical for crack sealing/filling performance. Flexibility and adhesion are important to maintain performance at low temperatures. Recently proposed test method, "Performance Based Sealant Grading (SG)" system, was adopted and performed using nine different sealants and fillers in this study. The results are shown in Table 4.18. Both CSBBR and direct tension tests were performed at different temperatures and the higher sealant performance grade from two test results was assigned as a final sealant performance grade. For most of sealant and filler, CSBBR results showed a higher grade than that from the direct tension test results.

The SG ranges from -34°C to -10°C. The relatively lower grades were obtained from RoadSavor 201, RoadSavor 222, Beram 195 and 3405 Reg., which are ASTM 6690 Type II and III materials. The relatively higher grades were assigned to PG 64-22 and AE-90S. Those are not common crack filling materials and were expected to have higher grade than crack sealants and fillers. Correlation between SG and the field performance of sealant and filler were examined by lineal regression analysis (refer to Ch. 4.3.2 for analysis details) and the results are shown in Table 4.19. Overall, the statistical analysis indicated that there was no strong correlation between the sealant performance grade and the pavement and crack performances with different types of sealants and fillers.

4.4 Summary

- Effectiveness of sealing/filling
  - Effectiveness of crack sealing/filling in terms of pavement and crack performances are presented in Table 4.20 and

TABLE 4.13
Comparison of Texture Scanner Changes between Crack Sealing/Filling and Untreated Sections.

Crack Sealing/Filling Section vs. Untreated Section	SR-43		US-52	
	Routed	Non-routed	Routed	Non-routed
AE-90S	0.738	**0.221**	0.661	**0.004**
Poly Flex	**0.003**	0.883	0.312	**0.047**
Fiber Asphalt	**0.030**	**0.211**	**0.012**	**0.004**
RoadSavor 201	**0.052**	0.167	**0.199**	**0.132**
RoadSavor 211	0.334	0.837	**0.045**	**0.003**
RoadSavor 222	**0.025**	0.220	**0.010**	**0.014**
Beram 195	**0.008**	**0.005**	0.476	**0.008**
3405 Reg.	0.123	**0.009**	**0.082**	**0.093**
PG 64-22	N/A	N/A	0.155	**0.062**
Percentage of the crack sealing/filling sections outperforming the untreated sections (based on average change)	**6/8 (75%)**	**8/8 (100%)**	**7/9 (100%)**	**9/9 (100%)**
	14/16 (88%)		**16/18 (89%)**	
	30/34 (88%)			
Percentage of the crack sealing/filling sections outperforming the untreated sections (based on p-value < 0.1)	**3/8 (38%)**	**4/8 (50%)**	**3/9 (33%)**	**9/9 (100%)**
	9/16 (56%)		**12/18 (67%)**	
	21/34 (62%)			

NOTE: Shaded cells represent the crack sealing/filling sections which outperformed the untreated sections.
Numbers are p-values; bold numbers indicate statistical significance (less than 0.1).

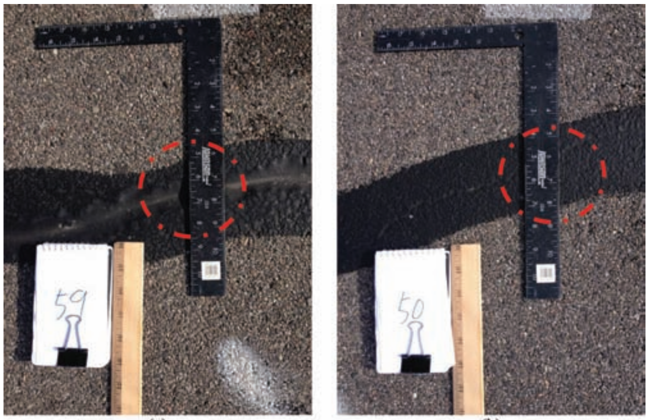
TABLE 4.14
Comparison of Texture Scanner Changes between Routed and Non-routed Sections.

Routed Section vs. Non-routed Section	SR-43	US-52
AE-90S	0.133	**0.067**
Poly Flex	0.154	0.820
Fiber Asphalt	**0.017**	**0.022**
RoadSavor 201	**0.051**	0.186
RoadSavor 211	0.279	**0.037**
RoadSavor 222	0.975	**0.001**
Beram 195	0.076	0.100
3405 Reg.	**0.025**	0.158
PG 64-22	N/A	0.134
Percentage of the routed sections outperforming the non-routed sections (based on average change)	**4/8 (50%)**	**1/9 (11%)**
	5/17 (29%)	
Percentage of the routed sections outperforming the non-routed sections (based on p-value < 0.1)	**1/8 (13%)**	**1/9 (11%)**
	2/17 (12%)	

NOTE: Shaded cells represent the routed sections which outperformed the non-routed sections.
Numbers are p-values; bold numbers indicate statistical significance (less than 0.1).

Table 4.21. In the tables, the average changes of the crack sealing/filling sections and the untreated section (the first row), the percentages of the crack sealing/filling sections outperforming the untreated sections (the second row), and the statistically significant percentage of the crack sealing/filling sections outperforming untreated sections for each test method (the third row) are presented.

- The IRI and surface crack evaluation results showed that the crack sealing/filling were effective. The average change of IRI in the crack sealing/filling section was 1.13 in./mile less than the untreated sections and crack sealing/filling sections outperformed the untreated section by 6 pp. The average crack length in the crack sealing/filling sections was 16.1 ft/100ft less than the untreated sections and 30 pp more crack sealing/filling sections outperformed the untreated sections in terms of the average crack length. The LTE and asphalt modulus results showed that the crack sealing/filling sections did not outperform the untreated section. Thus, the crack sealing/filling was determined to be effective in preventing pavement surface crack distress occurrence.



(a) (b)

Figure 4.21 Material shape: (a) routed crack; (b) non-routed crack.

- The UPV on crack and texture scanner results indicated that crack sealing/filling sections outperformed the untreated sections. The average change of UPV on crack in the crack sealing/filling sections was 36.4 µs less than the untreated sections. The average volume increase, based on the texture scanner results, in the crack sealing/filling sections was 0.49 in^3 less in the crack sealing/filling sections and 24 pp more crack sealing/filling sections outperformed the untreated section in terms of average volume increase. Thus, the crack sealing/filling was concluded to be effective in maintaining crack integrity and resisting sealant and filler deformations due to the seasonal crack movement.

- **Effectiveness of routing**

  - Effectiveness of Crack Sealing/Filling in terms of pavement and crack performances are presented in Table 4.22 and Table 4.23. In the table, the average changes of the routed sections and non-routed sections, the percentage of the routed sections outperforming the non-routed sections, and the statistically significant percentage of the routed sections outperforming non-routed sections for each test method.
  - The test results from IRI, LTE asphalt modulus, and pavement surface crack, showed that the routed sections did not outperform the non-routed sections. Therefore, the routing was not determined to be effective in terms of the pavement performances.
  - UPV and the texture scanner results indicated that the routed sections did not outperform the non-routed

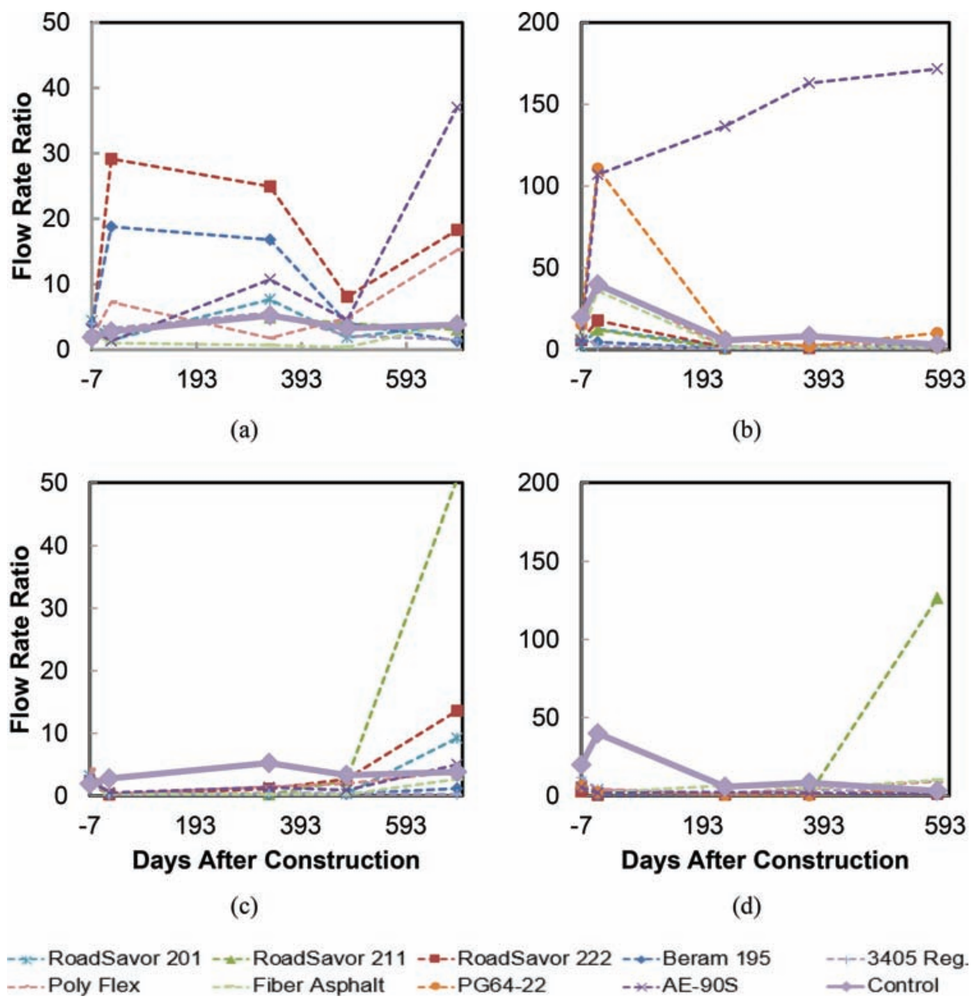


Figure 4.22 Flow rate ratio: (a) SR-43 routed section; (b) US-52 routed section; (c) SR-43 non-routed section; (d) US-52 non-routed section (Figures are not in the same scale).

TABLE 4.15
Relative Material Performance Ranking for Filling Application.

IRI		LTE		Asphalt Modulus		Surface Crack		ACS Failure		UPV on Crack		Texture Scanner	
Rank	Mat.	Rank	Mat.	Rank	Mat.	Rank	Mat.	Rank	Mat.	Rank	Mat.	Rank	Mat.
1	**PF**	**1**	**PG**	**1**	**211**	**1**	**PF**	**1**	**PG**	**1**	**201**	**1**	**222**
2	211	2	211	2	PG	**1**	**FA**	2	195	2	FA	2	195
2	201	3	PF	3	PF	2	PG	2	222	3	195	3	FA
2	PG	3	222	3	201	2	211	2	211	4	PG	4	PF
3	AE	4	AE	4	222	2	222	3	AE	4	AE	4	PG
4	3405	4	201	5	AE	3	3405	4	FA	4	3405	5	3405
4	195	5	195	6	3405	4	201	5	PF	5	PF	5	211
5	FA	6	3405	7	195	5	195	5	3405	6	211	6	AE
6	**222**	**7**	**FA**	**8**	**FA**	**6**	**AE**	**6**	**201**	**7**	**222**	**7**	**201**

NOTE: Shaded cells represent the best and worst performing sealant and filler.
AE-90S: AE; Poly Flex: PF; Fiber Asphalt: FA; RoadSavor 222: 222; Beram 195: 195;
3405 Reg.: 3405; RoadSavor 201: 201; RoadSavor 211: 211; PG 64-22: AB

TABLE 4.16
Relative Material Performance Ranking for Sealing Application.

IRI		LTE		Asphalt Modulus		Surface Crack		ACS Failure		UPV on Crack		Texture Scanner	
Rank	Mat.	Rank	Mat.	Rank	Mat.	Rank	Mat.	Rank	Mat.	Rank	Mat.	Rank	Mat.
1	**AE**	**1**	**PF**	**1**	**PF**	**1**	**195**	**1**	**222**	**1**	**211**	**1**	**PG**
2	222	2	3405	2	201	**1**	**AE**	2	201	2	PG	2	201
3	PG	2	201	3	222	2	201	3	211	2	FA	3	AE
4	201	3	195	4	3405	2	FA	4	PG	3	PF	3	222
4	3405	3	211	5	195	3	PF	5	195	3	201	3	PF
4	211	4	222	6	211	4	3405	5	FA	4	3405	4	FA
5	195	5	FA	6	PG	5	222	6	AE	5	222	4	3405
6	PF	6	AE	**7**	**AE**	5	211	6	PF	6	195	5	195
7	**FA**	**7**	**PG**	**7**	**FA**	**6**	**PG**	**7**	**3405**	**7**	**AE**	**6**	**211**

NOTE: Shaded cells represent the best and worst performing sealant and filler.
AE-90S: AE; Poly Flex: PF; Fiber Asphalt: FA; RoadSavor 222: 222; Beram 195: 195;
3405 Reg.: 3405; RoadSavor 201: 201; RoadSavor 211: 211; PG 64-22: AB

TABLE 4.17
Results of Linear Regression Analysis for Sealing Application.

Sealing/Filling Failure vs.	Parameter Estimate	Standard Error	P-value
IRI	-0.01207	0.021076	0.578459
LTE	-1.94569	1.935801	0.336443
Asphalt Modulus	-7.9E-05	0.002619	0.976412
Surface Crack	0.005596	0.00887	0.541028
UPV	0.001554	0.002499	0.546702
Texture Scanner	0.2062	0.200152	0.325029

sections. However, ACS failure result showed that the routed sections significantly outperformed the non-routed sections. The routed sections showed 46 pp less ACS failure than the non-routed sections and 65% of the routed sections outperformed the non-routed sections. As a result, the routing was determined to be relatively more effective in ACS failures.

- The mixed results regarding the effectiveness of the routing were obtained from the literature review and the field evaluation. Some literatures including the Illinois study reviewed in this study reported that the routing is effective and this study concluded that the routing was effective in minimizing ACS failures. However, the routing was not determined to be effective in terms of ride quality, structural integrity, pavement surface crack, crack integrity, and material deformation for two years in the test sections.

- **Material performance**

  - In terms of ACS failure, PG and RoadSavor 222 showed the best performances for crack filling and sealing applications, respectively. The test results indicated that ASTM 6690 Type II crack sealants performed relatively well in terms of pavement and crack performances.

TABLE 4.18
Sealant Grades from CSBBR and Direct Tension Tests

	AASHTO TP 87	AASHTO TP 88
	CSBBR	Direct Tension Test
RoadSavor 201	**-34 °C**	-34 °C
RoadSavor 211	-28 °C	**-22 °C**
RoadSavor 222	**-34 °C**	-34 °C
Fiber Asphalt	-28 °C	**-16 °C**
Poly Flex Type II	-28 °C	**-16 °C**
Beram 195	**-34 °C**	-34 °C
3405 Regular	**-34 °C**	-34 °C
PG 64-22*	**-10 °C**	-10 °C
AE-90S*	-16 °C	**-10 °C**

- The correlations between the ACS failure and the other tests were overall very poor with high P-values, which concluded that material performances (ACS failure) do not significantly influence the pavement and crack performance within a two-year period.

- **Sealant Grade Testing**
  - The statistical analysis indicated that there was no strong correlation between the sealant performance grade and the pavement and crack performances with different types of sealants and fillers.
  - INDOT currently uses ASTM Type II crack sealants, which showed an overall good pavement and crack performances from the evaluation. The correlation between sealant performance grade of each material and the pavement and crack performance test results were insignificant. Thus, the current INDOT crack sealant material selection process is concluded to be adequate.

TABLE 4.19
Results of Linear Regression Analysis for Both Sealing/Filling Application

Sealing/Filling Failure vs.	Parameter Estimate	Standard Error	P-value
IRI	0.811932575	0.70737023	0.277761303
LTE	-218.0264124	66.8990504	0.085881345
Asphalt Modulus	0.262367846	0.08663024	0.127076032
Surface Crack	-0.115803463	0.29861711	0.706291329
UPV	0.047541114	0.0840928	0.584301958
Texture Scanner	2.366726987	6.93172015	0.739842536
Sealing/Filling Failure	-7.378702384	9.97202646	0.476348703

TABLE 4.20
Effectiveness of Crack Sealing/Filling in Terms of Pavement Performance

Crack Sealing/Filling Section vs. Untreated Section	IRI	LTE	Asphalt Modulus	Surface Crack Evaluation
Avg. change	6.03 (7.16) in./mile	-0.02 (-0.04)%	-64 (-102.9) ksi	30.6 (46.7) ft/100ft
Percentage of the crack sealing/filling sections outperforming the untreated sections (based on average change)	53%	44%	24%	65%
Percentage of the crack sealing/filling sections outperforming the untreated sections (based on p-value < 0.1)	N/A	6%	9%	N/A

TABLE 4.21
Effectiveness of Crack Sealing/Filling in Terms of Crack Performance

Crack Sealing/Filling Section vs. Untreated Section	Sealing/Filling Failure	UPV on Crack	Texture Scanner	Flow Rate Ratio
Avg. change	N/A	15.8 (52.2) μs	0.24 (0.73) in^3	N/A
Percentage of the routed sections outperforming the non-routed sections (based on average change)	N/A	94%	88%	N/A
Percentage of the routed sections outperforming the non-routed sections (based on p-value < 0.1)	N/A	47%	62%	N/A

TABLE 4.22
Effectiveness of Routing in Terms of Pavement Performance

Routed Section vs. Non-routed Section	IRI	LTE	Asphalt Modulus	Surface Crack Evaluation
Avg. change	7.96 (-15.3) in./mile	-0.01 (-0.04)%	-58.19 (-69.81) ksi	26.8 (14.6) ft/100ft
Percentage of the treated sections outperforming the untreated sections (based on average change)	35%	47%	18%	47%
Percentage of the treated sections outperforming the untreated sections (based on p-value < 0.1)	N/A	27%	12%	N/A

TABLE 4.23
Effectiveness of Routing in Terms of Crack Performance

Routed Section vs. Non-Routed Section	Sealing/Filling Failure	UPV on Crack	Texture Scanner	Flow Rate Ratio
Avg. change	35 (81)%	24.8 (-19.1) μs	0.99 (0.9) in3	N/A
Percentage of the routed sections outperforming the non-routed sections (based on average change)	94%	71%	29%	N/A
Percentage of the routed sections outperforming the non-routed sections (based on p-value < 0.1)	65%	24%	12%	N/A

5. EXPERIMENTAL EVALUATION OF CRACK SEALANT AND FILLING EQUIPMENT

5.1 RapidRouter™

Crack cutting can be performed either by a diamond saw or a rotary impact router. With its productivity advantage and the ability to follow the crack more closely, the router is the most commonly used cutting procedure. RapidRouter™ (RR) is a skid steer mounted router as shown in Figure 5.1. RR is controlled from cab with skid loader control. An operator is in a safe environment with RR.

Figure 5.1 RapidRouter™.

5.1.1 Performance Evaluation

RR was evaluated for production rates, operation requirement and safety concerns by comparing to typical manual router used by INDOT.

5.1.2 Evaluation Plan

Routing operation with RR and manual router were performed by Columbus Sub-district on US-31 between N 650 and I-65 (exit 76) on June 09, 2014 (Figure 5.2). The test section had average annual daily traffic of 29,804 and four lanes.

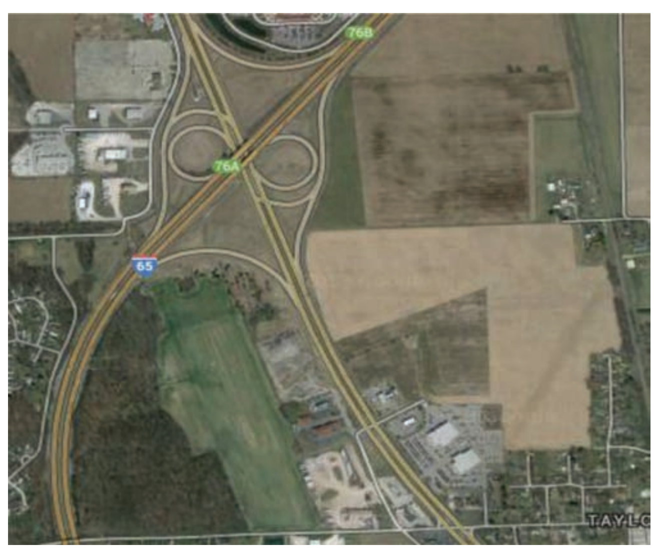


Figure 5.2 Test roads.

Figure 5.3 Field evaluation: (a) RapidRouter™; (b) manual router.

RR and manual router were evaluated on north bound passing lane and south bound passing lane, respectively. The length of each test section was 0.55 mile. Only transverse cracks were routed in the test sections. RR and manual router during evaluation are shown in Figure 5.3.

5.1.3 Evaluation Results

Field evaluation results are summarized in Table 5.1. Each router was operated by a trained crew. Reservoir dimension was set to be ½ in. by ½ in. and both routers resulted in proper accuracy for the reservoir dimension. The routing operation was monitored for 70 min. each and there was no downtime during the monitoring or any equipment problems. Average routing speed was between 20 and 40 sec per each full-lane with transverse crack for both RR and manual router. As a result, the total number of cracks routed for 70 min. was almost the same (i.e., 65 for RR and 66 for manual route). It was noted during evaluation that routing operation was much faster than cleaning and sealing operations. Thus, the cleaning and sealing operation speed was a dominant factor for sealing production rates in the evaluation. According to the interview with the operator, the main advantage of RR is that it is safer for operators and operation speed can be maintained throughout the operation as it does not require much physical labor unlike manual routing operation.

5.1.4 Summary

RR and the manual router had the similar production rates each other (20 to 40 sec/transverse crack) in about half-mile sections. RR can be a safer option in the crack sealing practice. According to SAC, the routing operation is widely considered to be the major factor affecting the production rates of crack sealing operation. However, the findings indicated that the routing operation was not a major factor. It should be noted that equipment related down-time could be main factor affecting the crack sealing operation as there have been numerous reports regarding issues with a router and sealant kettle maintenance.

TABLE 5.1
Summary of Field Evaluation Results

	RapidRouter™	Manual Router
No. of Equipment	1 + Skid Loader	1
No. of Operator	1	1
Avg. Routing Speed	20–40 sec. / transverse crack	20–40 sec. / transverse crack
# of Cracks Routed for 70 min	65	66
Safety	Safer*	

*According to the interveiw with the operator.

5.2 Hot Air Lance

A proper cleaning is very critical in crack sealing/filling performance as dust inside reservoir or pavement surface prevents material to be properly bonded to the surface. Routing operation generally creates a lot of dust and it is very difficult to clean especially when moisture is present in the surface as dust adheres to the moisture forming a thin dust barrier.

In general, there are six different crack cleaning methods, including compressed air, hot air lance, sawing, wire brush, pressurized water, and sand blasting. Manual of practice from Strategic Highway Research Program recommends the use of a hot air lance for removal of dust and moisture from the crack (Smith & Romine, 1999). According to the recent survey conducted as part of crack treatment for asphalt pavement synthesis study, 35% of the respondents indicated that the use a hot air lance (Decker, 2014).

Hot air lance burns vapor propane and mix it with compressed air in a combustion chamber. High velocity hot air is produced and directed towards the pavement surface. In general, hot air lance is capable of producing heated air at temperatures ranges from 600°F to 3000°F with exit speed of up to 3000 ft/s.

In prior to the evaluation, crack temperature changes after hot air lance application were monitored. The routed crack was cleaned with the hot air lance and the temperature change of the routed crack was monitored with an infrared camera, as shown in Figure 5.5. The air temperature was 70°F and the initial crack temperature was 82°F. The temperature of the routed crack increased to 109°F after hot air application and the routed crack temperature returned to its initial temperature of 82°F after 16 min, as shown in Figure 5.4.

5.2.1 Performance Evaluation

The primary objectives of this evaluation are (1) to present the development process of a hot air lance performance evaluation method; (2) to evaluate effectiveness of hot air lance under dry and wet condition.

5.2.2 Evaluation Plan

Adhesive bonding is a critical property that indicates sealant performance. In order to quantify the bonding strength with different surface conditions, the field pull-off test was performed in the evaluation.

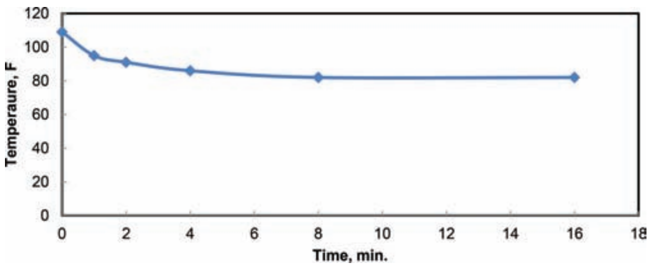


Figure 5.4 Crack temperature changes after hot air application.

5.2.2.1 Pull-Off Test. Pull-off test (ACI 506.4R and ASTM C 1583-04) is a type of tension test, which was originally developed to measure the quality of bond of new concrete pavement to existing concrete surface on concrete bridges and has been popularly used in concrete overlay QC/QA. Other standard and guidelines are also available from International Concrete Repair Institute and The Army Corps of Engineers.

5.2.2.2 Specimen Preparation. The standard test method (ASTM C 1583-04) specifies the epoxy adhesive material for bonding the steel disk to the concrete. Different types of epoxies were evaluated on the routed and sealed crack surface. Epoxies provided sufficient bonding between steel disk and epoxies, however, contact area between epoxies and crack sealing/filling material was too small. As a result, most failure occurred between epoxy and material.

To apply the pull-off test to crack sealing/filling material, proper bonding between steel disk and material was required. In this application, increasing contact area between steel disk and material would provide sufficient bonding even without using epoxies. As a result, it was determined to make a mold so the

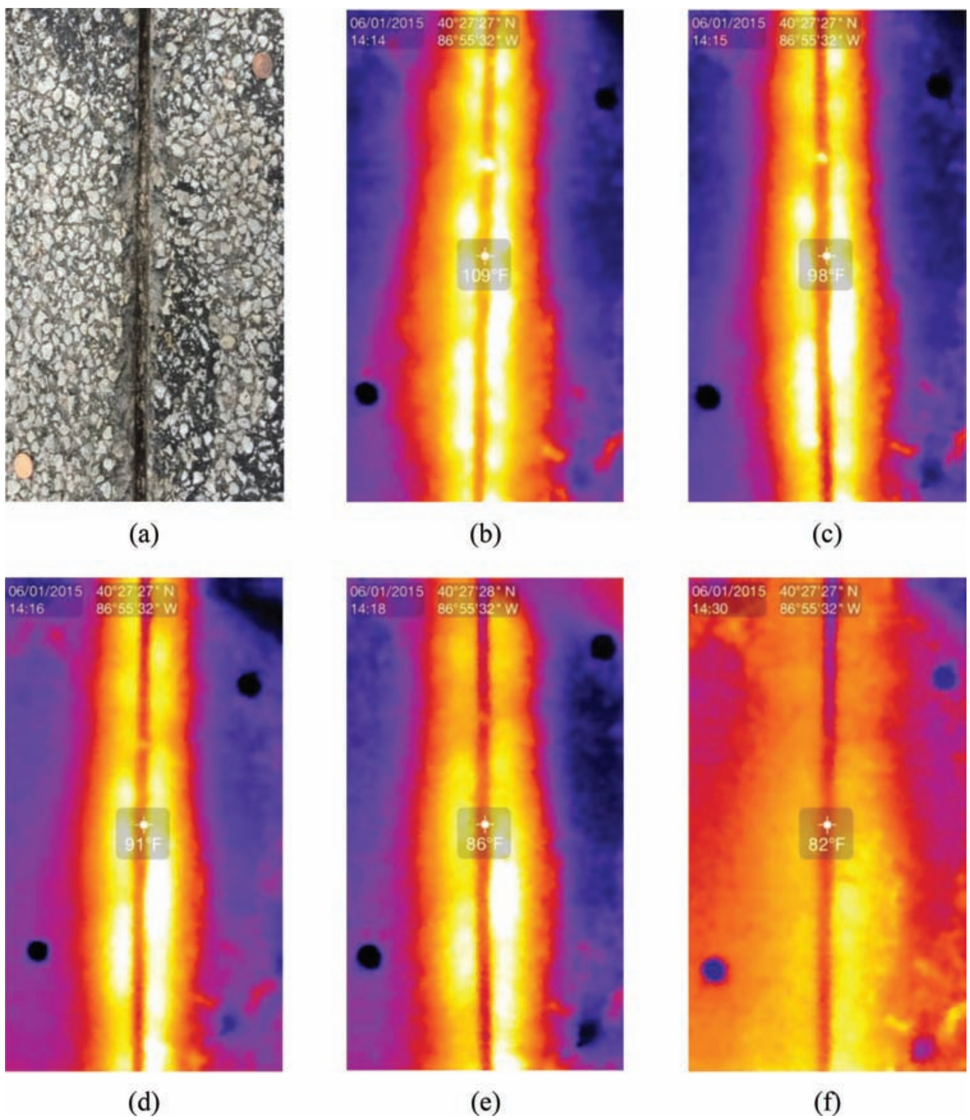


Figure 5.5 Crack temperature changes after hot air application: (a) crack; (b) after 0 min.; (c) after 1 min.; (d) after 2 min.; (e) after 4 min.; (f) after 16 min.

Figure 5.6 Pull-off test specimen (a) steel disk with crack sealant; (b) steel disk with epoxy at the bottom.

crack sealing/filling material can be held along with the steel disk. Successfully prepared specimen is shown in Figure 5.6 (a).

5.2.2.3 Test Temperature. Crack sealing/filling materials had good extendibility and the material did not fail when pull-off test was performed at unfreezing temperature, as shown in Figure 5.6 (b). In addition, adhesion at low temperature is a key to the performance as materials are prone to the failure at low temperatures. According to LTPPBnd (Version 3.1), low temperature in West Lafayette, IN, at 0.5 in. depth of layer with 50% reliability is -16.3°C (2.66°F). Thus, the test temperature was determined to be 2.6 ($\pm$1) °F.

5.2.2.4 Pull-Off Test Procedure. Details about the preparation and the pull-off test are the following:

- Mold Preparation: PVC pipe with inside diameter of 2.25 in. and 3 in. height is cut in half. Assemble the cut pipe mold into its original shape and apply a thin coat of Vaseline inside (i.e., a mold release agent).
- Mold Installation and Curing: Place the mold on the crack and secure it by applying silicon around the mold as well as in the crack. Silicon should completely fill the reservoir at each end of the mold so the material is contained. Silicon needs to be cured for at least one hour. (Figure 5.7 (a)).
- Material Placement and Disk Installation: Heat material up to manufacturer suggested application temperature and fill up to 3/8 in. from the pavement surface. It should be noted that this pouring height may need to change depends on the steel disk size. 3/8 in. was determined to be the optimum volume of material not submerging the steel disk upon installation. If too much material is poured into the mold, the steel disk would be completely submerged under the material. If too little material is poured into the mold, not enough contact area is formed between material and the steel disk (Figure 5.7 (b) and (c)).
- Demolding: Each specimen is cured to air temperature for one hour before removing the mold.
- Conditioning: Each specimen is covered with dry ice (32 oz. of crushed dry ice) and needs to be conditioned until the desired test temperature is reached. (Figure 5.7 (d)).
- Pull-off test: Once the testing device is properly attached to the steel disk then the tensile load is applied at a constant rate of 2 lbf per second. Failure mode (e.g. (a) failure between reservoir wall and material; (b) failure within material; (c) failure between steel disk and

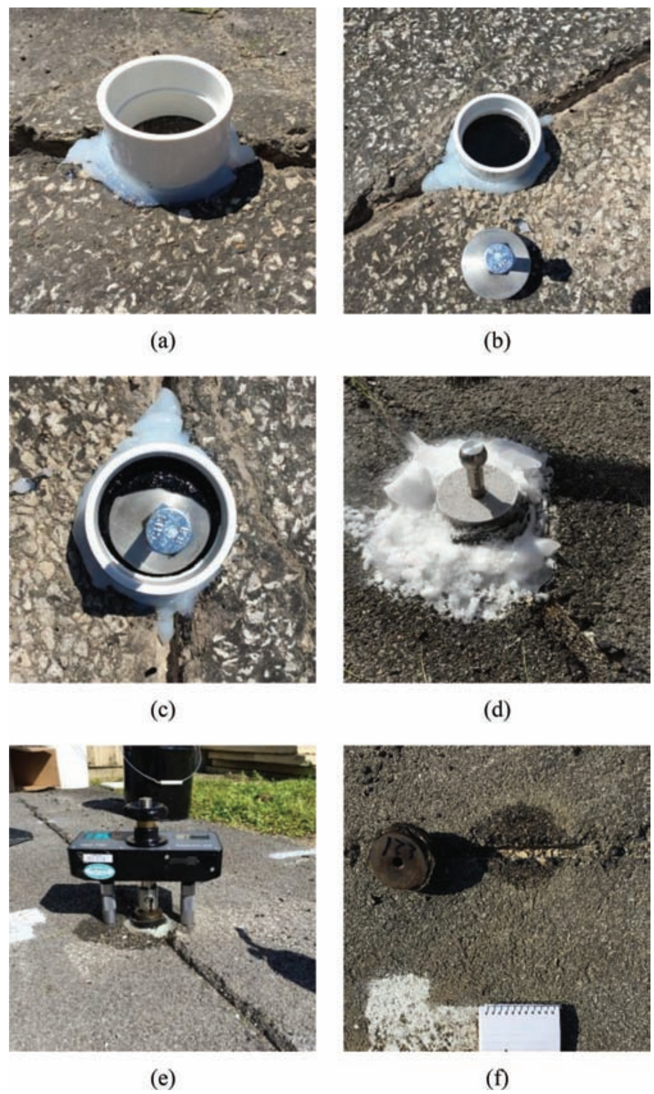


Figure 5.7 Field pull-off test (a) mold installation; (b) pouring material; (c) steel disk installation; (d) conditioning with dry ice; (e) pull-off test; (f) routed crack after test.

material) were recorded along with the tensile load in lbf at the moment of failure (Figure 5.7 (e)).

5.2.2.5 Test Site Construction. INDOT research division parking lot was newly paved in 2014 and did not exhibit any cracks. The construction began on May 28, 2015 and detailed procedures are the following:

- A 60 by 12 ft section was first selected and thoroughly cleaned using air compressor. Then 18 of 12 ft length lines were marked on the surface and each line was 3 ft apart. The test site schematic is shown in Figure 5.8. The test site is divided into two sections, dry and wet. For each subsection, 9 cracks were allocated into 3 subsections and 3 cracks were again selected for each subsection representing different heat treatment conditions. For example, dry cold subsection represents reservoirs in dry condition cleaned without using a hot air lance. Dry hot subsection denotes reservoirs in dry condition with heat treatment.
- 9 reservoirs in dry section were first constructed with a manual router (Model 30 Router from Crafco). The reservoir dimension was ½ by ½ in. Each reservoir was then cleaned. In order to minimize the effect of factors (e.g., nozzle type, pressure, etc.) other than the temperature affecting, the hot air lance with the wheel kit on was used for cleaning of both dry and cold subsections. Cleaning speed of 5 in./s to 6 in./s was maintained during the cleaning and the regulator for propane gas tank was set to be 20 psi.
- Each test spot was prepared for pull-off test based on the procedures.
- Once the construction of dry section was completed, water was applied to the wet section 3 times at a rate of 6 gallon/min.
- Routing operation in wet section began when there was no running water on the surface from the last (3rd) water application. Rest of the construction followed the same procedure used for dry section construction in 2 and 3. It should be noted that temperature and velocity of hot air lance could not be measured for the experiment and it also varies by literatures and ranges 1,000°F to 2,500°F and 2,000 fps to 3000 fps, respectively (35). During the cleaning, all valves were set t wide open for each cleaning, thus temperature and velocity were assumed to be consistent.

Figure 5.8 Test section prepared for pull-off test.

(a) (b)

Figure 5.9 Hot air lance evaluation equipment: (a) Sullair 185 air compressor, Crafco hot air lance form; (b) hot air lance application.

5.2.2.6 Equipment. For the test site construction, one portable air compressor, one hot air lance were used, and one 20 lb. propane gas tank, as shown in Figure 5.9. A larger propane tank (e.g., 100 lbs) may be necessary for a field application as to not be filling the tank every day. Air compressor used for the experiment was Sullair model 185, which was capable of delivering 185 cfm of air. It should be noted that the hot air lance model used for the evaluation recommend for uses with a greater than 50 CFM air compressor. The hot air lance was from Crafco featuring the maximum air discharge of 3000 ft/s and air temperature of 2,600°F. The hot air lance included the wheel kit which protects the operator from any flying debris during cleaning operation.

5.2.3 Results and Analysis

Pull-off test was conducted on June 01, 2015. Visual inspection was conducted on both failure modes to ensure that pull-off test measurements were only from samples with the failure occurring at the interface between reservoir wall and material. The typical failure mode of pull-off tests was the interface failure showing the debonding occurred at the interface between reservoir wall and material. Specimens after test from cleaned and control subsections are shown in Figure 5.10. To present the measurement distribution, the pull-off bonding strengths from dry and wet sections are shown in Figure 5.11.

Figure 5.11 shows that the dry section (328 lbf) has higher mean pull-off bonding strength than the wet section (122 lbf) regardless of the heat treatment type. Based on a t-test, it was confirmed that there was a significant pull-off bonding strength difference between the sections (i.e., P-value=0.0004). From each section,

(a) (b)

Figure 5.10 Specimen after test (a) specimen from cleaned subsection: (b) prematurely failed specimen from control subsection.

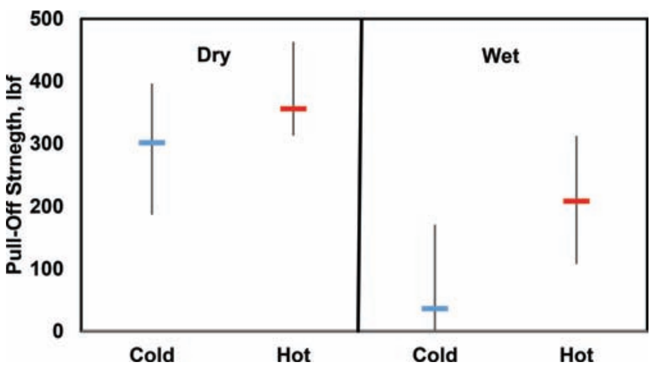


Figure 5.11 Pull-off bonding strength distributions of dry and wet section.

pull-off strength from heat treated subsections showed higher strength as well. Pull-off bonding strength of dry cold, dry hot, wet cold, and wet hot were 396, 463, 171, 312 lbf, respectively. T-test was conducted to determine the effect of heat treatment in each section and the p-value was 0.12 for dry section and 0.001 for wet section. In other words, the effect of heat treatment was not significant in dry condition, yet it was effective in wet condition. Consequently, the effectiveness of heat treatment was shown in this experiment, but only in wet condition.

5.2.4 Summary

The hot air lance effectively cleans and dries the wet cracks and provides better bonding between the materials and the asphalt pavement surface than the conventional air compressors. The cracks treated with HAL had 570% higher bonding with significant difference than the cracks treated with the conventional air compressor on the wet surface. However, there was no significant difference of bonding between those on dry condition. The incorporation of hot air lance in the wet condition is recommended to extend both the operation time during the day and available season for crack filling and sealing operation (2070 and 2090 activities).

6. CONCULSIONS AND RECOMMENDATIONS

To understand the current practice regarding crack sealing/filing application, literature review and nationwide and statewide surveys were conducted in 2012. The experimental evaluation was performed to assess the effectiveness of crack sealing/filling application, routing, material performance, and equipment performance. Five crack sealant and four crack filling materials were tested utilizing IRI, FWD, surface crack evaluation, adhesive/cohesive/spalling (ACS) failure, UPV, texture scanner, and flow rate. In addition, the new sealant grading system was evaluated with the same nine crack sealing/filling materials and the performance of RapidRouter^{TM} and hot air lace (HAL) were evaluated. The conclusions and recommendations, which were drawn based on the laboratory tests and field experimental evaluations (i.e., five data collections within a two-year period) are the following.

6.1 Conclusions

- Literature review and nationwide/statewide survey performed in 2012

  - Most state agencies used both sealing and filling terminologies interchangeably.
  - 65% of the responses indicated that the routing is required for the crack sealing/filling application.
  - ASTM D 6690 Type II was the most widely used material and only Missouri and Indiana included emulsions in their specifications as crack sealing/filling materials.
  - Over 70 products were listed in the approved/qualified product lists of 17 state DOTs.
  - Most of sealants and fillers are produced by Crafco, Deery, McAsphalt, and Right Pointe.
  - INDOT performed the crack sealing throughout the year and the crack filling was primarily conducted during the winter season.
  - Most INDOT Sub-districts shared crack sealing equipment available in their Districts and crack sealing/filling equipment availability and their maintenance were the most concerned problems.

- Effectiveness of crack sealing/filling

  - *Pavement performance:* The IRI and pavement surface crack evaluation showed that the crack sealing/filling sections performed better than the do-nothing section. It should be noted that the difference between average IRI changes over two years in the crack sealing/filling sections and the do-nothing section was 1.13. The LTE and asphalt modulus results showed that the crack sealing/filling sections did not outperform the do-nothing section. Thus, the crack sealing/filling was determined to be only effective in preventing pavement surface crack distress occurrence.
  - *Crack performance:* UPV on crack and the texture scanner results indicated that the crack sealing/filling sections outperformed the do-nothing section. Thus,

the crack sealing/filling was concluded to be effective in maintaining crack integrity and resisting sealant and filler deformations due to the seasonal crack movement.

- Effectiveness of routing

  - *Pavement performance:* IRI, LTE asphalt modulus, and pavement surface crack showed that the routed sections did not outperform the non-routed sections. It should be noted that the findings are based on a limited two-year field performance evaluation.
  - *Crack performance*: UPV and the texture scanner results indicated that the routed sections did not outperform the non-routed sections. However, ACS failure result showed that the routed sections significantly outperformed the non-routed sections.

- Material performance

  - In terms of ACS failure PG and RoadSavor 222 showed the best performances for crack filling and sealing applications, respectively. The test results indicated that ASTM 6690 Type II crack sealants performed relatively well in terms of pavement and crack performances.
  - The correlations between the ACS failure and the other tests were overall very poor with high P-values, which concluded that material performances (ACS failure) do not significantly influence the pavement and crack performance within a two-year period.

- Sealant grade

  - The correlation between the sealant performance grades and the pavement and crack performances with different types of sealants and fillers were poor and insignificant.

- Equipment performance evaluation

  - RapidRouter™: RapidRouter™ and the manual router had the similar production rates each other (20 to 40 sec/transverse crack) in about half-mile sections. RR can be a safer option in the crack sealing practice.
  - HAL: The cracks treated with HAL had 570% higher bonding between the materials and the asphalt pavement surface with significant difference than the cracks treated with the conventional air compressor on the wet surface. However, there was no significant difference of bonding between those on dry condition.

6.2 Recommendations

- Routing Practice

  - The mixed results regarding the effectiveness of the routing were obtained from the literature review and the field evaluation. Some literatures including the recent Illinois study reviewed in this study reported that the routing was effective and this study concluded that the routing was effective in minimizing ACS failures. In addition, crack movement in full depth asphalt pavements is not enough to need the routed reservoir according to SAC. As a result, it was recommended from the SAC meeting that routing in the 2090 Activity be limited to transverse cracks (reflective cracks) on AC over concrete pavements.

- AE-90S

  - The test section results show that there are some better performing sealants and fillers than AE-90S. AE-90S costs about 65% of the average cost of other sealants. However, considering the residue of emulsion (e.g., 65%), the sealants have competitive price. Therefore, replacing AE-90S with the other crack sealants or fillers for the filling application (2070 Activity) should be considered.

- Material Selection

  - INDOT currently uses ASTM Type II crack sealants, which showed an overall good pavement and crack performances from the evaluation. The correlation between the sealant performance grades and the pavement and crack performances with different types of sealants and fillers were poor and insignificant. Thus, the current INDOT crack sealant material selection process is concluded to be adequate.

- Hot Air Lance

  - The hot air lance effectively cleans and dries the wet cracks and provides better bonding between the materials and the surface of asphalt pavement than the conventional air compressors. The incorporation of hot air lance in the wet condition is recommended to extend the operable time and seasonal availability for crack filling and sealing construction (2070 and 2090 Activities).

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