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Research Article

Crack sealing vs crack filling: A state of the art review and analysis

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ABSTRACT

The objective of this paper is to evaluate existing literature regarding the practice of pavement crack treatment using crack sealing and crack filling technique. There are two methods of sealing water and other debris out of asphalt pavements: crack sealing and crack filling. Crack sealing uses a router to cut the crack to provide a uniform rectangular reservoir for greater penetration of sealants, thus allowing the sealant material more even contact with the asphalt pavement with less chance for air voids. On the other hand, there is no pavement removed with crack filling treatment. The following topics are discussed in this paper: crack sealing, crack filling, treatment procedure and equipment selection, treatment materials evaluations, material placement, pavement evaluation, Texas and other US states practices and traffic safety issues. The most cost effective practice between crack sealing and filling treatment can be analyzed via the selection of appropriate test sites, computer aided simulation, and life cycle cost analysis. Overall, the literature suggests a comprehensive review of all the known literature and conducted an analytical study of crack sealing and filling practices along with all those factors impacting sealant performance.

Keywords: Crack sealing, Crack filling, Routing, Reservoir, Router

1. Introduction

Cracking is an inevitable problem in asphalt concrete pavement and plays a large role in pavement deterioration. Cracks develop on the surface of the pavement and indicate a reduction in pavement integrity and serviceability. It is considered as one of the two main concerns in the pavement design process and the primary mode of deterioration in the pavement. Also, it is the main factor in determining time and method of rehabilitation. A crack occurs when a stress is built up in a pavement layer that exceeds the tensile or shear strength of the pavement materials. In order to delay pavement deterioration, extend service life and maximize shrinking public funds, there is no better way than doing pavement maintenance. There are various types of

pavement maintenance activities such as total surface seals, resurfacing, crack sealing or filling. The main goal of these surface treatments is to minimize the intrusion of water through cracks into underlaying layers which can lead to pavement structural failure. The different types of crack formation are recognized as transverse, longitudinal, fatigue, block, reflective, edge and slippage, and each has their own causes. Among these surface treatments, sealing the crack with sealant material has been a common pavement maintenance practice for decades.

Crack sealing is the process of routing and placing sealant material in the routed channel. This is opposed to crack filling, which is simply inserting sealant without performing any modification to the crack walls. Sealing cracks can reduce the water infiltration, prevent pumping and avoid the need for premature base and pavement repair. Although it has advantages, it can affect the pavement in many ways such as tracking of scaling material by tire action, reduced skid resistance and a rougher pavement. Sealing of crack is the logical alternatives compared with other maintenance program due to its economic benefits, improving serviceability and vital role in extending the life of pavement (Eaton et al., 1992). The practice of sealing cracks will keep improving in terms of the durability of sealants and its implementation techniques. Proper planning, design and implementation of sealing techniques can ensure the longevity of the pavement as well as maintain a higher standard of ride ability over a longer period of time.

2. Crack sealing and crack filling

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

Crack sealing is used to treat the active cracks which open in winter and close in summer, known as working cracks. According to National Guide to Sustainable Municipal Infrastructure (2003), working cracks are typically greater than 3 mm in width in the summer and 15 to 100 percent larger in the winter. According to NCHRP 784, “1999 LTPP report, FHWA defined the movement for “working” classification as 2.5 mm; however currently the value most commonly referenced is 3 mm or approximately 1/8". According to the Federal Highway Administration Manual of Practice, transverse cracks which are perpendicular to the traffic

direction are considered as working cracks and are often targeted for crack sealing (Zinke et al., 2005; Hand et al., 2000). Working cracks are routed to a predefined geometry, cleaned and materials are placed into it in order to prevent the intrusion of water into the pavement surface through the upper surface. Routes are generally given with a width to depth ratio of one or greater than one that can enhance the sealant performance (Wang et al., 1993; Ketcham, 1996; Khuri et al., 1992; Chang et al., 1998). This treatment can be more effective when applied to pavements which are in good condition with low to moderate crack density and where cracks show little or no branching (FHWA 1998). The treatment of sealing crack is widely used as a component of Pavement Management Systems (PMS), though is not a comprehensive treatment in and of itself (Hu et al., 2012). Successful implementation of both these treatment applications depend on the appropriate selection of pavement and material, crack preparation and crack sealant application.

3. Crack Types and Development

The intrusion of water causes various distress mechanisms which can lead to the damage of the pavement structure. Crack types include fatigue cracks, longitudinal cracks, transverse cracks, block cracking, reflective cracks, edge cracks and slippage cracks (Caltran, 2000; Miller et al., 2003).

Fatigue cracks

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

Longitudinal cracks

These types of cracks develop longitudinally along the pavement's centerline and are caused by thermal movement or by poorly constructed construction joints between adjacent travel lanes or between a travel lane and the shoulder. Longitudinal cracks are considered as 'non-working' cracks and generally be effectively treated by crack filling.

Transverse crack

Transverse cracks occur perpendicularly to the center line of the pavement. These types of cracks form due to the thermally induced shrinkage at low temperatures. Transverse cracks are considered as "working" cracks

and suitable type of distress for crack sealing.

Block cracking

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

Reflective cracks

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

Edge cracks

Edge cracks are crescent shaped or parallel cracks located within 0.3m to 0.6m of the outer pavement edge. These cracks caused by overloading at the unbound edge of the pavement, shear failure or erosion in the shoulder. It cannot be effectively treated with crack sealing.

Slippage cracks

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

4. Planning, Design & Implementation

4.1 Time of Year & Temperature

The time of year and ambient temperature plays a vital role during the application of crack sealing and filling treatment. Eaton et al. (1992) suggested three variables to consider before crack treatment which are: when the cracks at their best width, time of year when crews are available, temperature range for sealant application. For hot climates they recommended winter is best as the cracks are open and the highway crews are available, for colder climates late fall and early spring will give the best results. They concluded with a safe thump rule that colder months (4°C - 24°C) are appropriate for crack sealing. Yildirim et al. (2006) suggested that crack sealing should be done during the winter months when the cracks are open so that sealant can more easily penetrate the crack. They mentioned the temperature should be between 7°C and 18°C. According to National Guide to Sustainable Municipal Infrastructure (2003), crack treatment should be

performed in spring or fall when temperature are moderate and cracks are mid-course in their annual cycle. They also mentioned that summer can be a good option in terms of sealant installation due to the low humidity in asphalt concrete surface and morning temperatures are the highest. They concluded that the selection time is a compromise between the effect of crack movement on sealant performance and sealant installation. According to NCHRP report 784 (2014), the temperature for performing crack treatment is recommended 4°C -21°C because cracks become wider during cool temperature. Also, winter months are recommended for hot and southern climates for sealing of cracks based on their survey. Fig. 1 presents the effect of crack opening and time of work on sealant material based on crack or rout width.

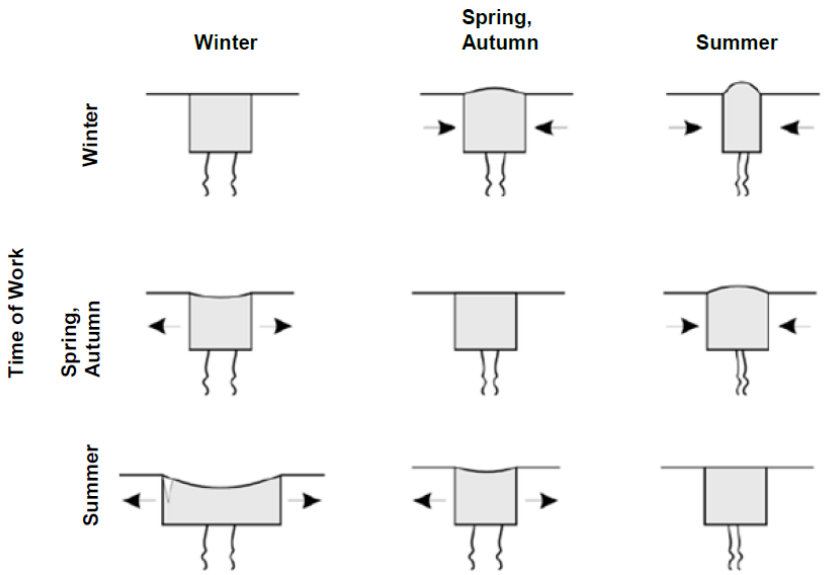

Fig. 1. Seasonal Impact on Sealing Operations (NCHRP Report 784)

4.2 Traffic Control

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

4.3 Safety Issues

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

4.4 Pavement Selection

Crack sealing can be a useful preventative maintenance activity if the selection of the pavement is suitable. The crack sealing and filling treatment should be carried out on structurally sound pavement which has low pavement distress (Guidelines for Sealing and Filling Cracks in Asphalt Concrete Pavement, 2003; Caltrans, 2009). According to SHRP-H-348 (1994) the pavement selection consideration should be based on pavement age, pavement and geometric design, pavement selection boundaries, traffic, type and extent of previous maintenance treatments and condition rating. It also suggested a shoulder survey should be performed on a small pavement selection, about 500 ft (153 m) in order to determine the amount, type and condition or severity of cracks, as well as the effectiveness of any previously applied crack treatments. According to Asphalt Crack Sealing Practices and Processes (Marpole and Ritchie, 2013), the best candidates for crack sealing and filling are newer pavements which are in the range of 1 to 3 years and the majority of pavement distress can be found in terms of longitudinal or transverse having slight to moderate crack density. According to Guidelines for Sealing and Filling Cracks in Asphalt Concrete Pavement (NGSMI, 2003), crack sealing and filling is first done on pavements that are three to five years old. Table 1 presents the description of crack width and density.

Table 1. Classes of Crack Widths and Densities (Chong et al., 1989)

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

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

Table 2. Crack Sealing Criteria

Crack Characteristics	Crack treatment			
	Caltrans cracking criteria	Yildirim et al. (2006)		NCHRP- 784 survey responses
		Routing	Non routing	
Width (inch, mm)	0.12-1.00, 3.1-25.4	0.2-0.75, 5.1-19.1	0.2-1.0, 5.1-25.4	0.24-1.01, 6.1-25.7
Depth (inch, mm)				0.72-3.00, 18.3-76.2
Edge Deterioration	<25%	Minimal to none ≤25% of crack length	Moderate to none ≤50% of crack length	
Annual Horizontal Movement	>0.12 Working	≥0.1	<0.1	
Type of Crack	Transverse Thermal Transverse Reflective Longitudinal Reflective Longitudinal Cold Joint	Transverse Thermal Transverse Reflective Longitudinal Reflective Longitudinal Cold Joint	Longitudinal Reflective Longitudinal Cold Joint Longitudinal Edge Distantly Spaced Block	
Time since last treatment				4.5 (years)

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

Table 3. Typical Pavement Condition Ratings (MTO 1990)

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

Zinke et al. (2005), mentioned that PSR numbers range from 1 (worst) to 9 (best) and PSR number of 6 to 7

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

4.5 Contracting Procedures

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

4.6 Sealing Methods

Selection of a placement configuration depends upon four variables.

a. Type of application or distress
b. Type of crack channel (cut or uncut)
c. Strike off or finish characteristics (Recessed, Flush, Capped, Band-Aid)
d. The dimensions of the crack channel

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

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

Flush-fill

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

Reservoir

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

Overband

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

Combination

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

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

Therefore, overband should be used only on low speed roads that will not be overlaid within in six months (Caltrans, 2009). Cheovits and Manning (1984) stated that overband configuration has disadvantages like aesthetics, exposure of the surface sealant to environmental and traffic deterioration and the large and localized tensile strain that develop above the crack. Also, Eaton and Ashcraft (1992) mentioned that overband

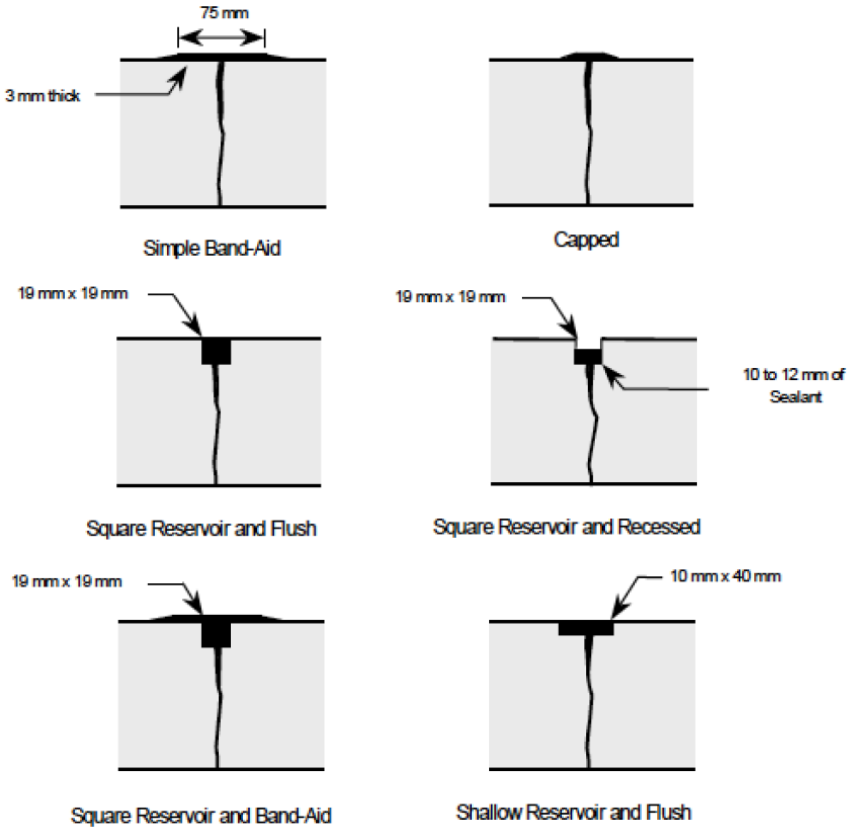

Fig. 2. Crack Sealing Techniques (Cuelho and Freeman, 2004)

Fig. 3. Squeegee for Sealant

should not be used on city streets, parking lots or sidewalks as the materials are prone to pick up due to traffic, resulting in material tracking. So, whether it is a routed or non-routed configuration, care must be taken to squeegee excess material off the surface after placing the sealants. Fig. 3 presents the squeegee for sealant.

Routing

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

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

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

Fig. 4. Carbide-tipped Rotary Impact Router Bit

Routs can be done either on a 1x1 profile (cutting as wide as deep) or 2x1 or 4x1 profile. Routing with 2x1 or 4x1 profile can follow meandering crack better (Eaton and Ashcraft, 1992). Routing with a width/depth greater than or equal to a ratio of one can enhance sealant performance but excessive widths is not desirable as it provide greater sealant exposure to slow moving traffic and raises failure rates (Marino, 1995; Masson et al., 1999). Good performance obtained with routs of 30 by 15, 25 by 12 and 12 by 12 [W (mm) x D (mm)] but rout width should not exceed 30 mm (National Guide to Sustainable Municipal Infrastructure, 2003). According to NCHRP Report 784 router should remove 1/8" from each side of the crack. The minimum and maximum widths of the cut are suggested as 1/2" and 1-1/2", respectively, with a recommended cut depth 3/4". Stevenson et al. (2001) recommended minimum reservoir width with recommended depths, for various climates. Table 4 shows the information.

Table 4. Reservoir Width & Depth (Stevenson et al., 2001)

Climate	Minimum Reservoir Width	Recommended Reservoir Depth
Warm	1/2" (12.7 mm)	3/4" (19.1 mm)
Moderate	3/4" (19.1 mm)	3/4" (19.1 mm)
Cold	1-1/8" (25.4-3.2 mm)	1/2" (12.7 mm)
Very cold	1-1/2" (25.4-12.7 mm)	3/8" (9.5 mm)

For milder climates Chong and Phang (1988) stated that a rout of 19 mm x 19 mm is also acceptable. Chong (1990) indicates that for urban expressway a rout configuration of 12 mm x12 mm works well. Ponniah and Kennpohl (2007) recommends routing cracks between 3 mm and 19 mm wide to a configuration of 40 mm x 10 mm. Filice (2003) recommends a 40 mm x 10 mm rout for transverse cracks and a 40 mm x 15 mm rout for transverse cracks where the pavement has a chip seal. Caltran Division of Maintenance (2009) recommends dimensions for routing and sawing. Table 5 presents recommended dimensions for routing.

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

Table 5. Recommended Crack Routing and Sawing Dimensions (Caltrans, 2009)

Nominal Crack Width*	Rout or Saw Width	Rout or Saw depth**	Width in Areas of Temp extremes	Depth in Areas of Temp extremes**
¼ inch (6.4 mm)	½ inch (12.7 mm)	½ inch (12.7 mm)	1 inch (25.4 mm)	½ inch (12.7 mm)
3/8 inch (9.5 mm)	½ inch	½ inch	1 inch	½ inch
½ inch (19.1 mm)	¾ inch (19.1 mm)	¾ inch (19.1 mm)	1 inch	½ inch
5/8 inch (15.9 mm)	¾ inch	¾ inch	1.5 inches (38.1 mm)	¾ inch (19.1 mm)
¾ inch (19.1 mm)	No routing required	¾ inch***	1.5 inches	¾ inch
7/8 inch (22.2 mm)	No routing required	¾ inch***	1.5 inches	¾ inch
1 inch (25.4 mm)	No routing required	¾ inch***	1.5 inches	¾ inch

*Nominal crack width is the approximate width for 80% of the length of the crack
**If using recessed fill method, add ¼ inch
***Use sand fill or backer rod to limit material depth to ¾ inch

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

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

4.7 Crack Preparations for Sealing

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

1. High pressure air blasting
2. Hot air blasting

3. Sand blasting
4. Wire brushing

High Pressure Air Blasting

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

Hot Air Blasting (HAL)

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

The color of the hot end of the HAL is a good indicator of its temperature. If it is bright orange to bright red, the temperature is 600°C to 1100°C; if it is dark red then 500°C to 600°C and if it is black then 400°C to 500°C. Caution must be taken so that overheating of the rout or crack should not take place. Overheating of the pavement leads to unnecessary hardening of the asphalt binder in the pavement adjacent to the crack resulting lower sealant adhesion (Masson et al., 2000).

Sand Blasting

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

Wire Brushing

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

4.8 Material Preparation, Application & Installation

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

Crack Sealants

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

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

Type 2: It is used for maintaining an effective seal in most climates, with low temperature performance tested at -29°C using 50% extension.

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

Type 4: Crack sealant used for maintaining an effective seal in very cold temperature, with low temperature performance tested at -29°C using 200% extension.

The two types of sealant most widely used are hot pour sealants and cold pour sealants. Hot pour sealant consists of asphalt cement with or without the addition of a modifier which must be heated to high temperatures in preparation for application. Rubber is the most common type of modifier which can increase the elasticity and melting point of the sealants. Hot pour sealants should be applied after cleaning the cracks and ensuring the pavement surface is free from moisture and dampness. Al-Qadi et al. (2009) recently

developed an evaluation for standard methods and procedures on sealants called performance-based grading system for hot pour sealant based on fundamental material properties. The sealant materials identified sealant grade in the same way as Super Pave PG asphalt binder grades. For example SG 76-16, where SG - Sealant Grade, 76 = the high temperature performance based on tracking resistance, ^{o}C; -16 = the low temperature performance based on stiffness, adhesion and cohesion properties, ^{o}C. Some modifications on rotational viscometer, vacuum oven aging, adhesion, direct tension and dynamic shear rheometer testing for sealant material are recommended.

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

4.9 Application of Sealants

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

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

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

Fig. 5. Hot Pour Crack Sealant Tank and Its Application

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

4.10 Material Finishes

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

4.11 Material Blotting & Curing

Blotting can be defined as the application of fine aggregate or sand to the non-cured sealant in order to prevent tracking (Yildirim et al., 2006). Clean and dry sand should be used to form a high quality blotter coat.

Caltrans recommended that brooming should not be done over a blotter coat because it leaves broom marks and voids in the sealant. Fine wood shavings can be used as a blotter coat because it is inexpensive, environmental and user friendly (National Guide to Sustainable Municipal Infrastructure, 2003). Rolls of toilet paper or hygienic paper should be avoided because the motorist may confuse them with white pavement markings. Cement dust should not be used as it can affect the sealant properties, pollutes, and may burn the skin on repeated exposure. The road should not be reopened to traffic until the sealant has cured.

5. Crack Sealing and Challenges

The sealant material should be selected carefully. On large projects, recommended testing should be performed on sealant materials. Overheating the material or heating the sealant material for prolonged period should be avoided. The solution is to monitor the temperature of the sealant in the kettle and remove the material which has been heated for longer periods of time. Prolonged heating periods for hot applied material range between 6 & 12 hours (Asphalt Crack Sealing Practices and Processes, 2013). Also it is recommended that any material left in the kettle at the end of the day should be removed and the kettle should be thoroughly cleaned. Improper cleaning of rout, over heating due to HAL while cleaning the crack, and damage to the pavement at the time of routing should be avoided. Crack sealing and filling treatment should be performed on younger pavements which are more susceptible to transverse and longitudinal cracking. For successful crack treatment, the working personnel need to understand the importance of the activities and the method of application. Although many agencies depend on on-the-job-training, but in the lack of uniformity in the on-the-job-training suffers when works needs to get done in a timely manner. Contractors and municipalities are responsible for ensuring proper training among their respective personnel.

6. Quality Control

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

Climatic Conditions

Ambient temperature should be at least 40°F (4.4°C) and rising.

Make sure fog or dew is not present.

Early morning operations should be in direct sunlight.

Routing

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

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

Guards and safety mechanisms on equipment should work properly.

Router should follow cracks without difficulty.

Routs on asphalt concrete pavement should be free of spalling.

Material Preparation

Melter should be empty and no material should be reheated.

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

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

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

Material safety data sheet (MSDS) should be available on-site.

Cleaning of Cracks & Routs

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

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

Make sure oil and moisture filters on compressor work properly.

Temperature of the hot-air lance should be below 930°F (499°C) and the tip should be placed 2 to 4 inches from the crack or rout.

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

Crack or rout should be free from moisture.

Sealant Application

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

The material should be applied to the inside of the cracks

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

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

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

Sealant Protection

Hot pour sealant surface should be covered with fine aggregate or sand without using broom

Traffic should not be opened until sealant is set.

7. Performance Evaluation

The performance life of a treatment mostly depends on the preparation of crack and the type of the material used (FHWA, 1999). One inspection should be made each year to chart the rate of failure and plan for subsequent maintenance. A midwinter evaluation is highly recommended as it will indicate treatment effectiveness when there is maximum pavement contraction and the crack is near the maximum opening (FHWA, 1999; SHRP-H-348, 1994). A small representative sample of the pavement, minimum of 150 m length should be selected for the evaluation. The following are common treatment failures which include-

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

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

8. Cost Effectiveness

Crack treatments can be considered as effective if it delays pavement deterioration and extends the pavement service life. Generally, the effective treatment extends the pavement life by two to five years (Evart et al., 1998; Chong, 1990). According to Chong and Phang (1988) the effectiveness of rout and seal maintenance depends upon three points: (a) Performance of the sealant materials and appropriate rout width and depth; (b) restraining of crack development and delaying the existing pavement distress; and (c) crack treatment implication period. Eaton and Ashcraft (1992), stated that chip seal treatment cost 3-14 times more than crack

sealing and an overlay cost 8-26 times as much as crack sealing. Also, Wang et al. (2012) concluded that sealing of cracks extend the pavement life approximately 1.7 years.

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

9. Evaluation of Alternatives

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

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

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

10. Crack sealing practices in TxDOT districts

A survey of crack sealing and crack filling procedures was developed and distributed in Texas. The response was received and analyzed. Texas does not currently require routing, but decides on a case by case basis whether it is needed. Questionnaires were sent to 25 districts, response were received from 20. In Texas, no district practice routing however one of the responses (Amarillo) provided that they have routing practice in the past but leave it due to time consumption and equipment issue. Durability of crack sealant application

Table 6. Crack Sealing Practices within Texas

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

varied from 3-5 years. However, 40 percent district do not have field evaluation for measuring the crack sealing performance. All those districts that responded, six of them stated that blowing out the debris from cracks with air has seemed to get them clean enough to seal and ensured good success with current method. Five districts responded that crack sealing with routing is a costly practice. Other districts mentioned that this practice is uncommon and do not have proper guidelines. Also, one district stated that they do not have any idea about its benefit. Responses to the questionnaire are provided in Table 6.

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

11. Out of province practices

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

A map has been made based upon the routing practices in different states. Fig. 6 illustrates the map where states with routing practice included in crack seal specifications. Also, a Table has been developed based upon

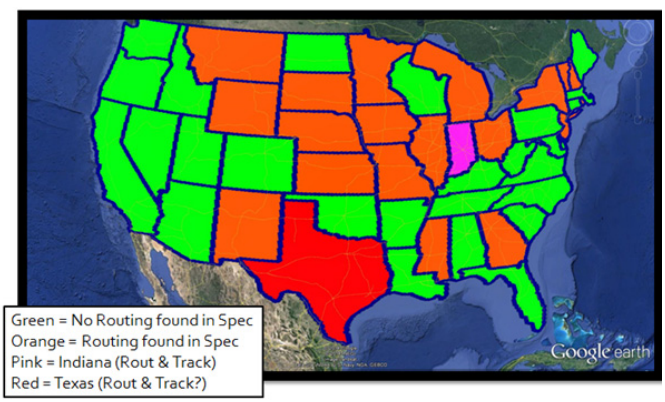

Fig. 6. States with Routing Practice

the investigation performed on the state specification. Information on out of province practices are provided in Table 7.

Table 7. Crack Sealing (Routing Configuration) Practices Outside Texas

State	Crack seal Spec. No	Routing included in spec#	Routing Spec# No	Config.1 (W) x (D) in.	Config.2 (W) x (D) in.	Ambient °F (°C)	Filling Criteria (D) in.	State Unit prices	Crack Seal price	Routing Price
Montana	403	Yes	403.03.2	3 / 4 x 3 / 4	1 / 2 x 1.5	>35 (1.7)		Yes	Yes	No
Wyoming	403	Yes	403.3.2	1 / 2 x 1 / 4				Yes	Yes	No
Rhode Island	408	Yes	408.02.1	1 / 2 x 1 / 2			-1/8			
Indiana	408	Yes	408.05	3 / 4 Max − 3 / 4 Min			-1/4	Yes	Yes	Yes
New York	412	Yes	412.7601 0004	3 / 4 x 3 / 4	1 / 2 x 1 / 2	>40 (4.4)		Yes	Yes	No
New Jersey	401.03.01.C	Yes	No				-1/4 - flush	Yes	Yes	No
Mississippi	413	Yes	No					No	No	No
New Mexico	411	Yes	No	1 / 2 x 3 / 4	1 / 2 x 1	>40 (4.4)	-3/8 to -1/4	Yes	Yes	No
Kansas	835	Yes	No	5 / 8 x 5 / 8	3 / 4 x 3 / 4	40-85 (4.4-29.4)	Slightly recessed	No	No	No
Iowa	2541	Yes	No	3 / 8 x 1 / 2		>40 (4.4)	Slight overfill	Yes	No	No
Missouri	413.50	Yes	No	1 / 2 x 1 / 2		>40 (4.4)		Yes	No	No
New Hampshire	413	Yes	No	3 / 4 + 1 /8 x 5 / 8		>50 (10)	-1/16 to -1/8	Yes	No	No
Georgia	408	Yes	No	1 / 2 x 1 / 2	1 / 2 x 3 / 4		-1/2	No	No	No
South Dakota	350	Yes	No	3 / 4 x 3 / 4	7 / 8 x 7 / 8	>45 (7.2)	Slight overfill	Yes	Yes	No
Nebraska	519	Yes	No	1 / 2 x 3 / 4	1 / 2 x 1			Yes	Yes	No
Illinois	451	Yes	No	3 / 4 x 3 / 4	1:1		Slight overfill	Yes	No	No
Michigan	502	Yes	No			45-85 (7.2-29.4)	-1/8-flush	Yes	Yes	No
Ohio	423	Yes	No	3 / 4 x 1				Yes	Yes	No
Vermont	417	Yes	No	3 / 4 x 3 / 4		40-104 (4.4-40)	Flush	Yes	Yes	No

12. Conclusions and Recommendations

The paper has reviewed the state of the art practices of crack sealing and crack filling treatment. There is a very limited literature considering the benefits crack sealing treatment over crack filling in terms of cost effectiveness and its impact to the pavement performance. Initial analysis based on the survey and specifications demonstrated that the time consumption, equipment issue, initial cost and lack of guidelines or knowledge are the actual reasons behind not using crack sealing treatment very often. Further research and field study focusing on the comparison between crack sealing and filling treatment is required in terms of performance and cost effectiveness. An accurate estimation can be measured by following proper guidelines while installing both this treatment types in the same test section.

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