DEPARTMENT OF TRANSPORTATION

Cost/Benefit Analysis of the Effectiveness of Crack Sealing Techniques

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16. Abstract (Limit: 250 words)
Crack sealing is an important preventive treatment in the pavement preservation program. To achieve a cost-effective crack seal, it is important to select a proper crack sealing method. While Minnesota usually seals cracks in asphalt pavements, there is no clear consensus on the most appropriate crack sealing method for a specific job. This study focused on developing a guideline so that a cost-effective crack sealing method could be chosen based on pavement type, functional condition, pavement age, and traffic volume etc. This study includes a literature review, online survey, field performance data collection and analysis, and development of a guideline. The effectiveness of the crack seals was determined using a benefit-cost analysis. Two decision trees were developed for choosing the most appropriate crack sealing method. The first, which can be used in MnDOT's pavement management system, needs information such as crack severity, pavement type (new vs overlay), pavement analysis period and design life, traffic level, and crack seal occurrence number. The second decision tree, which is a simplified version of the first and can be used by the preventive maintenance crews and requires less information: crack severity, traffic level, and crack sealing occurrence number.

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COST/BENEFIT ANALYSIS OF THE EFFECTIVENESS OF CRACK SEALING TECHNIQUES

FINAL REPORT

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EXECUTIVE SUMMARY

Sealing and filling cracks in asphalt pavements are important preventive maintenance treatments for achieving a good service life. Properly implemented crack sealing and crack filling can minimize the intrusion of water into the underlying layers of pavements. This can reduce moisture-related damages. Improperly implemented crack sealing may experience premature failure, can become ineffective in the reducing intrusion of water into the pavement structure. This may result in severe distresses, like stripping of asphalt and potholes, etc. In Minnesota, working cracks of asphalt pavements are repaired by sealing, and non-working cracks are repaired by filling. Working cracks, which mostly run in the transverse direction, are those that open in the winter and close in the summer due to thermal expansion and contraction of the surrounding pavement. Non-working cracks are those that do not undergo notable changes in width between seasons. Non-working cracks mostly develop in the longitudinal direction, typically due to pavement fatigue failure within the wheel path, or at the lane joint because of the weak or less-dense asphalt. The most commonly used crack sealing methods in Minnesota to repair asphalt pavements are clean-and-seal and rout-and-seal. In the clean-and-seal method, cracks are treated by blowing out the debris and then sealing the cracks with rubber sealant materials. In the rout-and-seal method, a reservoir is routed, centering it above the existing cracks before pouring the sealants. Between the above-mentioned two crack sealing methods, the rout-and-seal method is approximately two times more expensive than the clean-and-seal method and relatively time-consuming. Even though some studies indicate that rout-and-seal is superior to its counterpart, the actual cost-effectiveness of either of these seal methods is not yet fully understood. While the application of crack filling for non-working cracks is a widely accepted protocol, transportation agencies do not have a universally accepted guideline for selecting the most cost-effective crack sealing method for a specific job. Cities, counties, and MnDOT districts thereby do not follow a uniform procedure; some agencies prefer rout-and-seal, while others believe in clean-and-seal. The current study is aligned to provide a solution to the problem mentioned above so that a guideline is available for transportation agencies to refer to when selecting the most cost-effective crack sealing method based on the factors that can influence the performance of the seals.

The main objectives of this study are (i) to compare the service life and cost-effectiveness of the two crack sealing methods mentioned above and (ii) to develop a criterion to select the most appropriate crack sealing method based on pavement type, functional condition, pavement age, and traffic characteristics, etc. The abovementioned objectives were accomplished by performing the following major tasks: (i) literature review on crack sealant practices, (ii) crack sealant performance data collection and analysis, (iii) performance- and cost-effectiveness analysis, and (iv) development of a recommendation. Various literature on the crack sealant practices and performances, including research reports, synthesis, journal articles, and other relevant publications, were reviewed. The crack seal performance data was collected through an online survey and reviewing the history of crack sealing projects documented in several pavement construction data logs of the Minnesota Department of Transportation (MnDOT). Direct field performance data was collected through periodical evaluations of crack seals at 35 different sites located throughout Minnesota. The performance of the crack seals was studied by quantifying the performance index of the crack seals. The effectiveness of the crack seals was studied with respect to a benefit-cost analysis. Two decision trees were developed to guide transportation

agencies when selecting the most appropriate crack sealing method. The major specific conclusions drawn from the different tasks of this study are listed below:

- Between the two crack seal methods, it was found that rout-and-seal (of transverse cracks) is more commonly used in Minnesota.
- While there are no uniformly accepted criteria, currently the most commonly reported criterion for selecting a sealing method is crack/pavement conditions followed by pre-determined schedules. A good percent of practitioners does not follow any criteria at all.
- Regarding the failures of the crack seals, it was found that most of the crack seals in Minnesota fail by adhesion and it occurs during the winter season. This failure is being seen more commonly with wider crack spacing. Crack sealants either do not stretch enough or the adhesiveness achieved between the sealant and crack face is not strong enough to offer resistance against the tensile stress generated on the sealant in winter. Some cohesion failures were also observed but in very limited quantities. A good amount of spalling failure was also observed at some rout-and-seal sites.
- The crack seal performance data was collected from 35 inspection sites, which were then used to develop a direct correlation (R^2 = 0.95) between the average performance index and age of the seals. The correlation was useful to determine the average service lives of the rout-and-seal and clean-and-seal methods.
- It was found that the rout-and-seal and clean-and-seal methods have approximately 4- and 3-year service lives, respectively. These service lives were determined using the data collected in this project, as well as other relevant crack seal performance data found in the literature. The short-term performance for closely spaced cracks on a rural road is, however, identical for both clean-and-seal and rout-and-seal.
- The life-cycle cost analysis (LCCA) and benefit-cost ratio analysis showed that rout-and-seal is slightly more effective than the clean-and-seal, due to its longer performance period. However, if only a short-term benefit is considered, then clean-and-seal may be more cost-effective than its counterpart.
- Because the difference in benefit-cost ratios between the two crack sealing methods was not significant, several other decision factors were considered to establish the effectiveness of each crack seal method. Various factors, such as treatment cost, expected life, ease of operation, practitioners' opinion, and traffic level, were considered in addition to the benefit-cost ratio.
- Two decision trees were developed for choosing the most appropriate crack sealing method. The first one, which can be used for pavement management systems, needs information, including crack severity, pavement type (new vs. overlay), pavement analysis period and design life, traffic level, and crack seal occurrence number. The second decision tree, which is a simplified version of the first and can be used by preventive maintenance crews, needs less information: crack severity, traffic level, and crack sealing occurrence number (first time, second time or third time).
- In general, the clean-and-seal method was found to be appropriate for high crack severity conditions. The choice between rout-and-seal and clean-and-seal for low and moderate crack severity is found to be varied based on pavement age and type, traffic levels. The clean-and-seal method is found to be appropriate for sandy soil subgrades and the low initial budget scenario; whereas, the rout-and-seal method is preferred for clayey and silty subgrades, irrespective of other variables.

CHAPTER 1: INTRODUCTION

The goal of a pavement preservation program is to extend the pavement service life and enhance the state-wide performance in the most cost-effective way possible. Some of the preventive maintenance treatments within the framework of the pavement preservation program are crack sealing and crack filling, chip sealing, fog sealing, thin overlays, rut filling, etc. Johnson (2000) stated that the preventive maintenance is six to ten times more cost-effective than a “do-nothing” maintenance strategy. The benefit of preventive maintenance is a substantial saving of life-cycle cost as well as achieving an extended period of acceptable driving conditions. Among the various preventive maintenance treatments, the crack sealing and filling are the two most commonly used treatments performed on asphalt concrete pavements in Minnesota.

Properly implemented crack sealing and crack filling can minimize the intrusion of water into pavements’ underlying layers and reduce moisture-related damages. Improperly implemented crack sealing may lead to the development of premature failure, seals become ineffective in reducing the intrusion of water into the pavement structure, which may results in severe distresses, like stripping of asphalt and pothole, etc. Figure 1.1 presents two photographs demonstrating the difference in performance between an effective and ineffective crack seals. In Figure 1.1 (a), it can be seen that water could intrude into the pavement structure through the failed or ineffective sealant; whereas, the intact or effective seal in Figure 1.1 (b) was able to stop the intrusion of water.

In Minnesota, the working and non-working cracks are repaired with sealing and filling, respectively. Working cracks, which mostly run in the transverse direction, are those that expand in the winter and contract in the summer due to thermal expansion and contraction of the surrounding asphalt. These cracks, popularly known as thermal cracks, do initiate in the winter months due to the contraction of the asphalt in the surface layer. Non-working cracks are those that do not undergo notable changes in width between seasons. Non-working cracks mostly develop in the longitudinal direction typically due to pavement fatigue failure within the wheel path, or at the lane joint because of the weak or less-dense asphalt. Figure 1.2 and Figure 1.3 show typical examples of transverse and longitudinal cracks.

In Minnesota, the most frequently used crack sealing methods to repair asphalt pavements are clean-and-seal and rout-and-seal (Figure 1.4). In the clean-and-seal method, cracks are treated by blowing out the debris and then sealing the cracks with rubber sealant materials. In the rout-and-seal method, a reservoir is prepared by centering the existing cracks, and then sealants are poured. Among the two crack sealing methods mentioned above, the rout-and-seal method is approximately two times more expensive than the clean-and-seal method and relatively time-consuming. Even though some studies indicated the rout-and-seal is superior to its counterpart, the actual cost-effectiveness of either of these methods are not yet fully understood. While the application of crack filling on the non-working cracks is a widely accepted protocol, transportation agencies do not have a universally accepted guideline for selecting the most cost-effective crack sealing method for a specific job. Cities, counties, and Minnesota Department of Transportation (MnDOT) districts thereby do not follow a uniform procedure; some agencies prefer the rout-and-seal while the others believe in the clean-and-seal methods. Due to this, pavement engineers often face the challenge of choosing the most appropriate crack sealing method for their job.

(a) Failed Crack Seal (b) Intact Crack Seal

Figure 1.1 Photographs Show the Benefits of Effective Crack Seal

Figure 1.2 Photograph of a Transverse Crack

Figure 1.3 Photograph of a Longitudinal Crack

The Decision Tree available in MnDOT's Pavement Preventive Maintenance Guide provides a guidance on selecting different preventive treatments, as shown in Figure 1.5. The decision tree has provision for the crack sealing and crack filling treatments; however, it does not provide any guidance to choose between the clean-and-seal and rout-and-seal. The current study is aligned to provide a solution to the above-mentioned problem so that a guideline is available to the transportation agencies to refer to select the most appropriate crack sealing method based on the factors that can influence the performance of the seals.

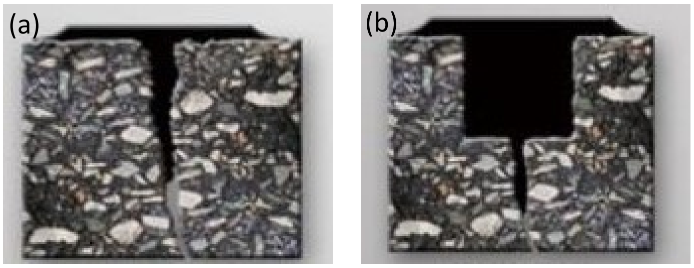


Figure 1.4. Crack Sealing Methods: (a) Clean-and-seal (b) Rout-and-seal, After Stoikes (2017)

1.1 OBJECTIVES AND TASKS

The main objectives of this project are (i) to compare the service life and cost-effectiveness of different crack sealing methods and (ii) to develop criteria to select the most cost-effective crack sealing method as a function of pavement type, functional condition, pavement age, and traffic characteristics, etc.

The abovementioned objectives were accomplished by performing the following major tasks: (i) reviewing the literature on the crack sealant installation practices and sealant performances; (ii) collecting and analyzing crack sealant performance data; (iii) conducting performance and cost-effectiveness analysis; and (iv) developing recommendations. The recommendations include decision trees for choosing the effective crack sealing method. Two decision trees were developed: one for the pavement management system, which can be added to the Minnesota Department of Transportation's (MnDOT's) existing 'Pavement Preventive Maintenance Decision Tree' shown in Figure 1.5. The second one is a simplified version of the former and can be used by the maintenance crew.

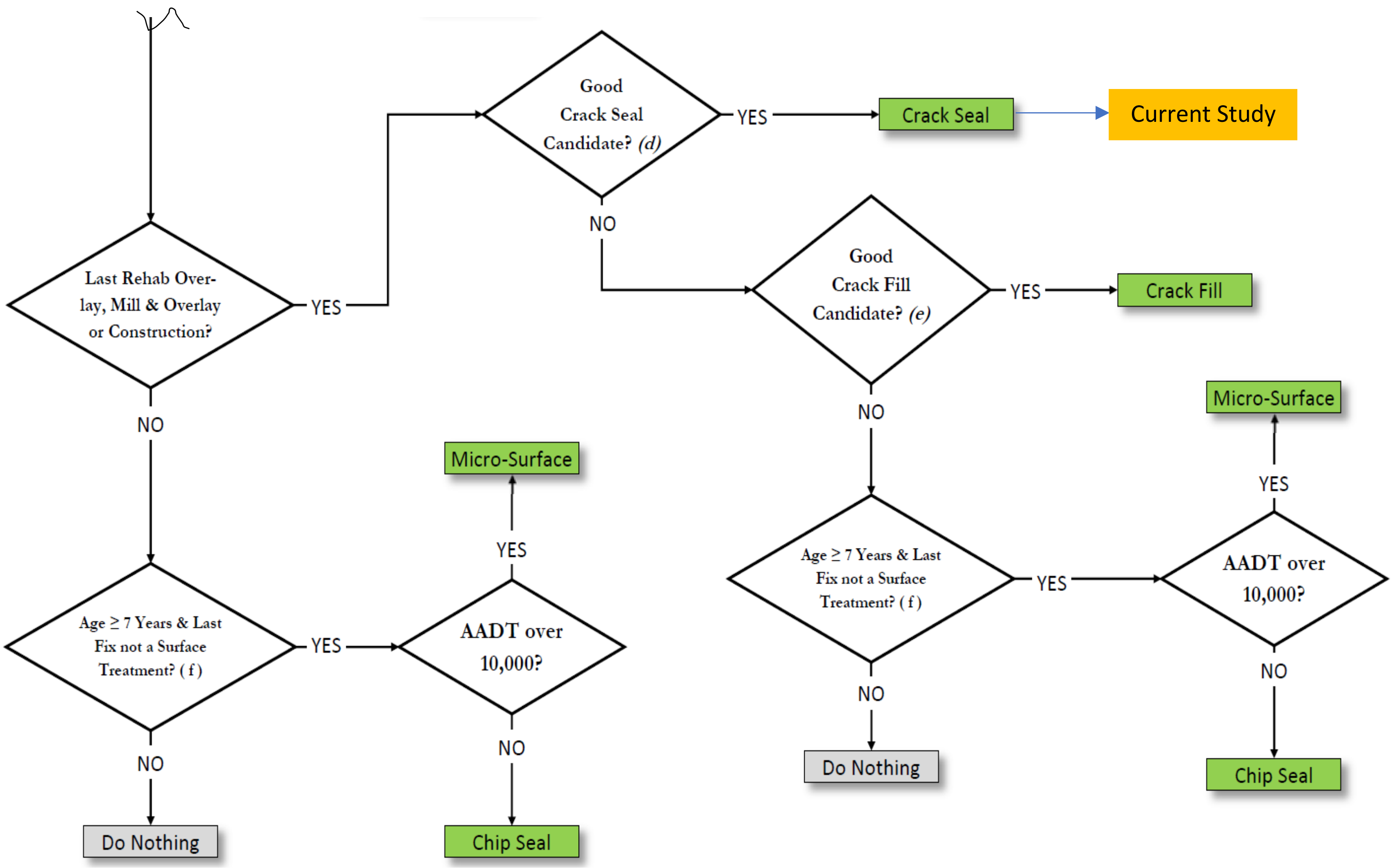


Figure 1.5. Part of MnDOT's Pavement Preventive Maintenance Decision Tree (Crack Treatment) (MnDOT 2018a)

CHAPTER 2: CRACK SEALING PRACTICES AND SEALANTS

2.1 CRACK SEALING

Crack sealing in asphalt concrete pavement is a preventive maintenance practice and is used throughout the country. The process of crack sealing involves placing a non-permeable rubber sealant into an existing crack in the wearing course of asphalt concrete pavement. Various construction and installation techniques are used by different states across the country to achieve the goals of crack sealing.

Applications of crack sealing vary throughout the country. In Minnesota, crack sealing is mostly used on working cracks. Working cracks are those that open in the winter and close in the summer due to thermal expansion and contraction of the surrounding pavement. Working cracks typically develop in the transverse direction. Smith and Romine (1999) defined working cracks as those that meet a 3 mm movement criteria.

2.2 CRACK FILLING

Crack filling techniques are often used on non-working cracks. Non-working cracks are those that do not undergo notable changes in width between seasons. Non-working cracks mostly develop in the longitudinal direction typically due to pavement fatigue cracking or lane joint separation. Transverse cracks may, however, be referred to as non-working if their spacing relative to each other is close enough that no significant changes in crack width will occur due to thermal expansion and contraction of the surrounding pavement. The goal of crack filling is not necessarily to prevent water from entering a crack but to support the surrounding pavement. The fill does, however, impede some water from entering cracks.

2.3 DIFFERENCE BETWEEN CRACK SEALING AND CRACK FILLING

While crack sealing and crack filling are two different processes with different goals in mind, it is often difficult to distinguish between working and non-working cracks in the field. For this reason, some states, such as Colorado, do not distinguish between the two for all of their in-house sealing projects. In the Colorado Department of Transportation (CDOT), Trunschke et al. (2014) noted that Colorado uses a single operation for its sealing contracts that conforms to more of a "filling" activity than a "sealing" activity. Minnesota does distinguish between the two and often uses different sealing and filling procedures on various cracks throughout a project. Although there is a little distinction, and often contradicting views on the differences between crack sealing and crack filling, Smith and Romine (1999) describe them as follows in the FHWA Materials and Procedures for Sealing and Filling Cracks is Asphalt-Surfaced Pavements Manual of Practice.

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."

Due to working cracks constantly undergoing changes in width, sealing requires the use of higher quality materials and more sophisticated construction equipment and processes; crack sealing, therefore, has a greater cost involved. If performed effectively and in a timely manner, crack sealing can improve pavement performance and extend its serviceable life. Limiting the volume of water entering a crack minimizes the risk of freeze/thaw related damage caused by water expanding and contracting in a crack, as demonstrated in Figure 2.1. Limiting incompressible materials from entering a crack allows free movement of the road to expand during warm weather. Otherwise, incompressible augment the compressive forces on the asphalt materials during the summer, as demonstrated in Figure 2.2. By restricting water and incompressible debris from entering cracks, properly placed seals extend the pavement life by keeping cracks from progressing in severity.

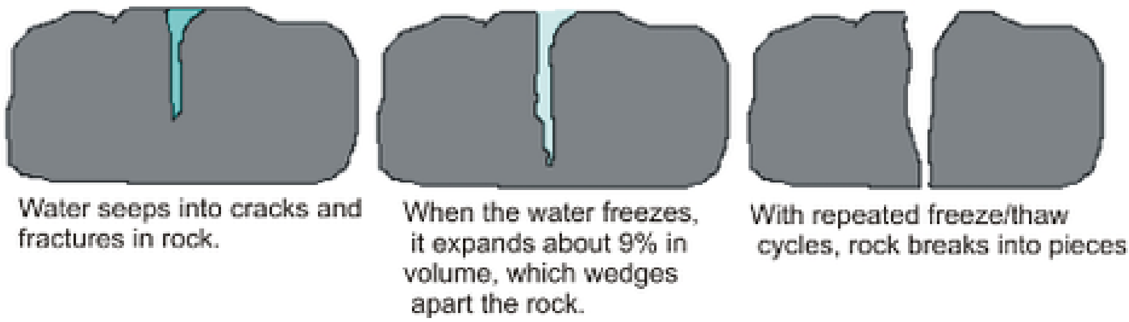


Figure 2.1: Freeze/Thaw Related Damage Caused by Water Expanding and Contracting in a Crack (after, Schulte, 2018)

Figure 2.2: Incompressibles Intrusion Related Damage (after, Stoikes, 2017)

2.4 INSTALLATION SEASON

Crack sealing in Minnesota mostly takes place during the spring, summer, and fall months. Installation season influences the seal performance due to different crack widths at different seasons. Sealing a working crack while it is partially closed during the summer months allows a minimal amount of material into the crack. A seal that is placed flush with the surface of the road during the summer stretches in the winter as the pavement contracts, then returns to flush the following summer. If the winter creates too large of a drop in air temperatures, cracks experience large opening and cause the adhesive or cohesive failure of the seal. Likewise, if a seal is placed flush to the pavement surface during the fall or spring, the seal would protrude from the crack. Figure 2.3 demonstrates the effects of crack expansion (during winter) and contraction (during summer) on a seal placed during the spring and fall months. Due to the reasons mentioned above, crack sealing is not recommended to be performed during the winter months. The seal would likely fail quickly due to excessive material loss and seal degradation. The other reason for not sealing during the winter is that the Minnesota climate presents a great challenge for proper crack preparation (cleaning and drying) during the winter months.

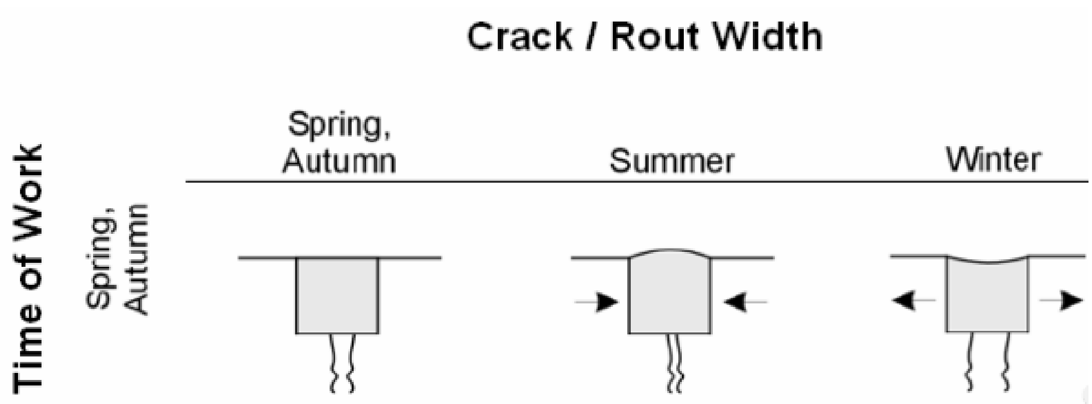


Figure 2.3: Crack Sealed in Spring and Corresponding Profile Views during Summer and Winter (after, Johnson, 2000)

2.5 CRACK SEALING EQUIPMENT

Crack sealing operation demands a wide range of equipment for sealant preparation, crack preparation, sealant installation, and sealant finishing. Some of the most common pieces of construction equipment for crack sealing are summarized below.

2.5.1 Crack Preparation Equipment

Airblaster: Airblasting is done with a high-pressured air compressor placed on a truck with hoses and wands. High-pressure blasting is fairly effective at removing dust and debris. Its downside is that it is not effective in drying the crack channel. Air blasting may also be performed with leaf blowers, but most states do not allow it due to a lack of air velocity and poor cleaning results associated with it. Figure 2.4 shows an example of air blasting to clean a crack.

Air Lance: Hot air blasting uses air that is heated to a minimum of 1,370° Celsius as defined by the Smith and Romine (1999). This form of cleaning is effective at removing dirt and debris. It also creates a dry and hot crack surface for a sealant to bond to. A hot surface will likely create a better bond for the sealant by activating the binder in the pavement itself. Caution must be used, however, as it is possible to burn the asphalt concrete pavement with a lance. For this reason, an open flame torch should never be used for this procedure. Figure 2.5 shows an example of an air lancing to clean a crack.

Figure 2.4: Airblaster Being used to Clean a Crack (after, Smith and Romine, 1999)

Figure 2.5: Airlance being used to Clean a Crack

Sandblaster: Sandblasting is a highly effective way of removing debris and loosened fragments from the channel of a crack. One pass of the sandblaster should be made on each side of a routed reservoir. The procedure leaves a smooth and textured surface that is ideal for the sealant to bond to. Sandblasting consists of a compressed air unit, sandblaster machine, hoses, and a wand. A second pass with an air compressor is typically necessary to clean any debris that was left during the sand blast. Due to the number of passes needed, sand blasting requires a great deal of equipment, is labor-intensive, and time-consuming. Figure 2.6 shows an example of sand blaster being used to clean a crack.

Figure 2.6: Sandblaster Being Used to Clean a Crack (after, Smith and Romine, 1999)

Figure 2.7: Wire Brush

Wire Brush: In this cleaning method, power-driven wire brushes are used in conjunction with some form of compressed air. This combination effectively removes debris from the crack but fails to remove loose pieces of the asphalt. Wire brushes are available with and without blowers. Some contractors have had success modifying pavement saws to fit wire brushes in place of the saw blade. Figure 2.7 shows an example of a wire brush used for cleaning cracks.

***Routing Machine*:** Crack routing is performed by a worker using a router or saw unit mounted onto a cart. The operator uses his/her eyes and best judgment to follow the path of the crack with the routing or sawing machine. Smith and Romine (1999) noted that although a saw with a 150-200 mm diameter diamond blade can follow the meanders of cracks fairly well, the high cutting rate of an impact router creates smoother reservoir walls with a higher percentage of aggregate area for the sealant to bond to. Most companies require that employees operating routing equipment wear some type of respirator mask. The most modern routing machines have air and dust control systems built into them. Figure 2.8 shows an example of a router in operation.

Figure 2.8: Routing Machine (after, Smith and Romine, 1999)

2.5.2 Sealant Preparation Equipment

Melter: Hot pour sealant is heated in a double-walled heating tank that uses a heat transfer oil, such that no flames come into direct contact with the tank holding the sealant. The Federal Highway Administration (FHWA) recommends that the melter should allow an operator to regulate the sealant temperature up to 220^{o}C (428^{o}F). The ideal heated temperature of each sealant material is typically specified on the package label. Upon being heated, the materials will transform from a solid state to a liquid state. Some melters have a recirculation feature, which is important to prevent temperature stratification within the tank and maintain a proper temperature for the sealant being laid into cracks. Upon reaching the desired temperature, the material is stored in the tank until it is placed into the crack. Figure 2.9 shows an example of a melter.

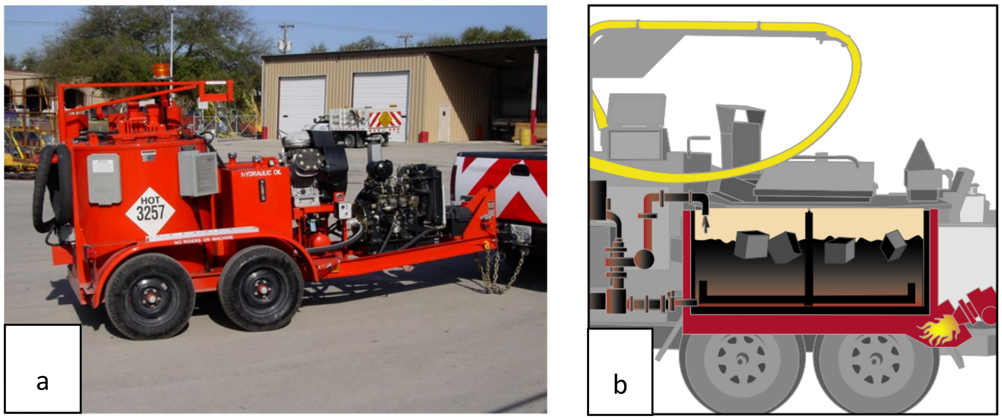


Figure 2.9: Melter

Distribution Hose: A melter truck has various distribution hoses connected to the back of it. The sealant flows through these hoses in order to be applied into cracks. A distribution hose may have a precision tip or may be equipped with a squeegee type nozzle that shapes the material in addition to applying it into the crack. A metal distributor may also be used to level off the poured sealant if no squeegee is present. Figure 2.10 shows an example of a distribution hose with a precision tip.

Figure 2.10: Distribution hose with a precision tip

Figure 2.11: Blotter Application

Blotter Applier: Application of a paper blotter material (typically toilet paper), occasionally soapy water, is used to prevent fresh sealant material from sticking to passing vehicle tires. Figure 2.10 shows an example of a blotter application.

2.6 SEALANT INSTALLATION

According to Smith and Romine (1999), crack sealant installation consists of at least two and up to five steps. These steps are:

1. Crack cutting (routing, sawing, etc.)
2. Crack cleaning and drying
3. Sealant preparation and application
4. Sealant finishing and shaping
5. Blotting

The two essential steps that every treatment process must consist of include (i) crack cleaning and drying, and (ii) sealant preparation and application. The following subsections describe the various installation steps usually adopted in different crack sealing methods: clean-and-seal and rout-and-seal.

2.6.1 Sealant Installation in Clean-and-Seal Method

It is the quickest and simplest form of crack sealing. It involves using a hot air lance or compressed air to blow debris from a crack, then filling it with a sealant. It is noted that clean-and-seal may often be confused with filling, but they are two different treatment procedures, mainly differ in the quality of sealant material used for the treatment. A higher quality sealant material (Type II: 50% extension at -20^{o}F) with better bonding characteristics is preferred for clean-and-seal (applied on transverse cracks) to withstand the thermal expansion and contractions during winter. A lower graded sealant material (Type I: 50% extension at 0^{o}F) would be sufficient for crack filling (applied on longitudinal cracks) due to the nature of non-working cracks. It is noted that the crack preparation (blowing or air lance) is usually the same for both treatment methods. It is recommended by Johnson (2000) that clean-and-seal be performed while cracks are still narrow and during the spring and fall seasons when temperatures are moderately cool. Figure 2.12 shows a photograph of a candidate transverse crack before and after being sealed using the clean-and-seal method. It is not advised to implement this sealing method on cracks that feature secondary cracking or edge deterioration at the crack face. Traffic should be re-routed during the construction process, and material should be allowed to cure before being re-opened to traffic. If the pavement must be re-opened immediately, a blotter material should be applied to prevent the sealant from being picked up by vehicle tires.

According to Johnson (2000), a clean-and-seal method is expected to perform for three years before a significant amount of materials begin to pull from the side of the crack. The seal will still perform at this point, as it still prevents some water and solids from entering the crack. Often, a second clean-and-seal may be applied on an existing clean-and-seal after the original seal begins to pull apart.

2.6.1.1 Equipment Needed

The clean-and-seal method of crack sealing requires the least amount of heavy equipment. Unlike rout-and-seal and saw-and-seal, no cutting or sawing machinery is required in this method. This method requires the following equipment:

Crack Preparation Equipment (at least one of the following): Airblaster, Air lance, Sandblaster, and Wire brush, etc.

Material Preparation: Melter

Material Application and Blotting: Distribution hoses, Shaping tools (squeegee, metal distributor), Blotting paper

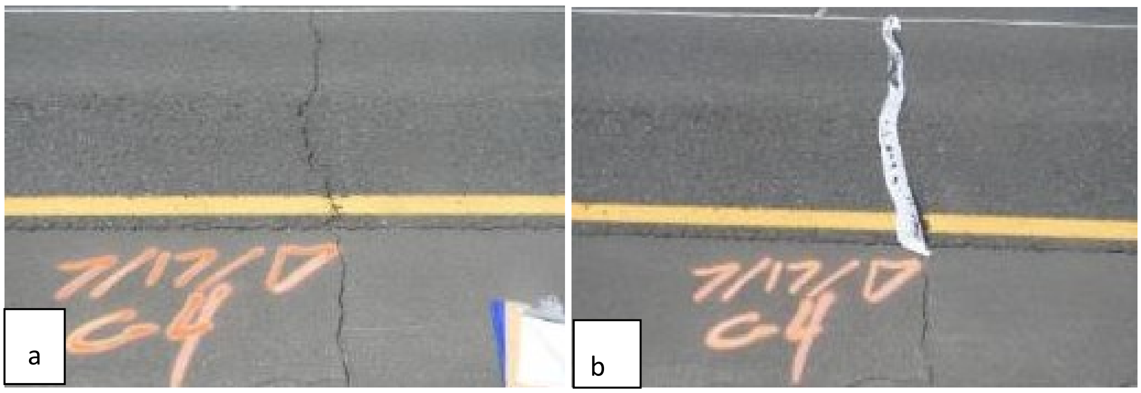


Figure 2.12: Clean-and-seal (a) before and (b) after sealant installation

2.6.1.2 Crack Preparation

Cleaning of the crack channel is an extremely important part of the crack sealing process, as a poorly cleaned crack will have a poor bonding surface for the sealant that is being applied. A high percentage of seal failures are adhesion failure that occurs due to the application of sealants on poorly cleaned or moist crack channels. Cleaning can include air blasters, hot air blasters (air lance), sandblasters, and wire brushes.

2.6.1.3 Sealant Preparation

The two types of sealants typically used to seal cracks in asphalt concrete pavement are hot-applied thermoplastic bituminous materials and cold-applied thermosetting materials. Both hot-applied and cold-applied materials may also be referred to as hot pour and cold pour materials. Upon reaching the desired temperature, the sealant is stored in the tank until it is placed into the crack.

2.6.1.4 Sealant Placement and Finishing

Sealant placement occurs through hoses and wands that extend from the back of the heater truck. In this placement process, a truck driver stops just past each crack, while a worker operates the hose and wand to fill the cracks. Trucks will often have multiple hoses and workers following them. For clean-and-seal, the hot pour sealant is placed directly into and over the crack. The placement can be finished with the same wand used for application or by the use of a metal distributor. Upon the seal being laid flat against the surface of the pavement, a blotter material may be applied to prevent the sticky seal from being pulled up by vehicle tires. Typical blotter materials include toilet paper and soapy water. Figure 2.13 shows a cross-section view of sealant placement in clean-and seal crack repair. It is advised that all seals should have time to cure prior to experiencing tire wear. If the road must be opened immediately, a blotter material is relied on.

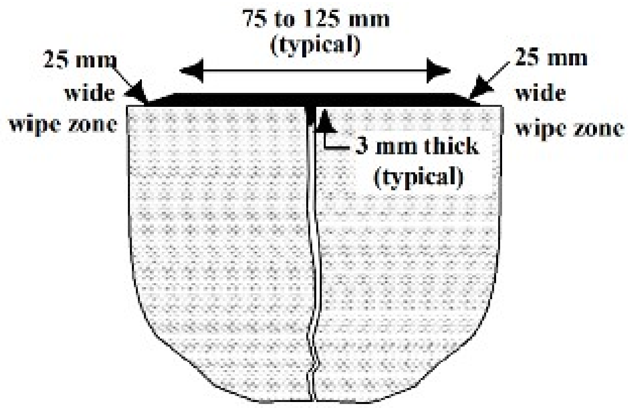


Figure 2.13: Cross-Sectional View of Clean-and-Seal (after, Smith and Romine, 1999)

2.6.1.5 Labor Needs and Cost

Clean-and-seal is the least labor-intensive form of crack sealing practiced in Minnesota. It typically requires two trucks; one for crack preparation and one for sealing. The trucks will each require a driver. The crack preparation truck is typically accompanied by 1-3 workers operating the air blaster or air lance. The melter will also be accompanied by 1-3 workers operating the sealant applicators and blotting material. A select number of workers are also required for traffic control. Since clean-and-seal is also the fastest crack sealing method used in Minnesota, it requires a much fewer number of work hours. Johnson (2000) stated that the unit price for clean-and-seal typically ranges between $0.10 and $0.30 per linear foot, depending on the size of the project.

2.6.2 Sealant Installation in Rout-and-Seal Method

Rout-and-seal is used on transverse cracks. It involves using a router or pavement saw along the length of a crack to create a reservoir centered over the existing cracks. The reservoir is then filled with a sealant. In the MnDOT's *Best Practices for Asphalt Pavement Maintenance Handbook*, Johnson (2000) recommends performing rout-and-seal early in the pavement's life to be successful. It states that if the cracks are too badly deteriorated or too wide, consider filling them rather than sealing them. The handbook does not directly state how wide is too wide, but it does recommend cutting a ¾-inch x ¾-inch reservoir. The reservoir should have a flush sidewall, that is, the crack should not be so wide or deteriorated that the saw or routing blade does not constitute the entire area of the reservoir.

There are three major benefits of creating the reservoir. One benefit is that the saw routing machine removes a percentage of deteriorated material from the immediate area around the existing crack. This reduces the possibility of water entering hairline secondary cracks around the existing crack and causing continues deterioration. The second benefit of cutting a reservoir is that it creates a very cleanable and sealable surface. It is much easier for workers to blow debris out of a fresh cut reservoir than an existing crack with various irregularities in its geometric shape. The consistently clean sidewalls made by routing are a good surface for a sealant to bond to. The third and largest benefit of routing cracks is that the reservoir holds a large pool of sealant that has a larger ability to expand and contract with the pavement due to thermal fluctuations. See Figure 2.14.

Figure 2.14: Routed Seal Expanding and Contracting Without Failure (after, Stoikes, 2017)

MnDOT specifies that rout-and-seal works best when performed in the spring and fall when temperatures are cool. The MnDOT's *Best Practices for Asphalt Pavement Maintenance Handbook* suggests that, if performed at the right time, a rout-and-seal can be expected to perform for three years before significant amounts of sealant begin to pull from the side of the reservoir. The seal will still perform after three years, however, since it still does prevent some incompressible material and water from entering the crack. The manual states that a project in Ontario has shown that rout-and-seal adds a minimum of two years and an average of five years to the life of a pavement.

2.6.2.1 Equipment Needed

Rout-and-seal requires additional pieces of equipment when compared to clean-and-seal. The extra equipment, a router, is used for making routs over the cracks being sealed. The remaining equipment is as same as the ones required for clean-and-seal method.

2.6.2.2 Crack Preparation

The first step of performing the rout-and-seal crack treatment is routing the cracks. Routing machinery comparable to that shown in Figure 2.8 is used for this. Figure 2.15 shows a crack before and after being routed.

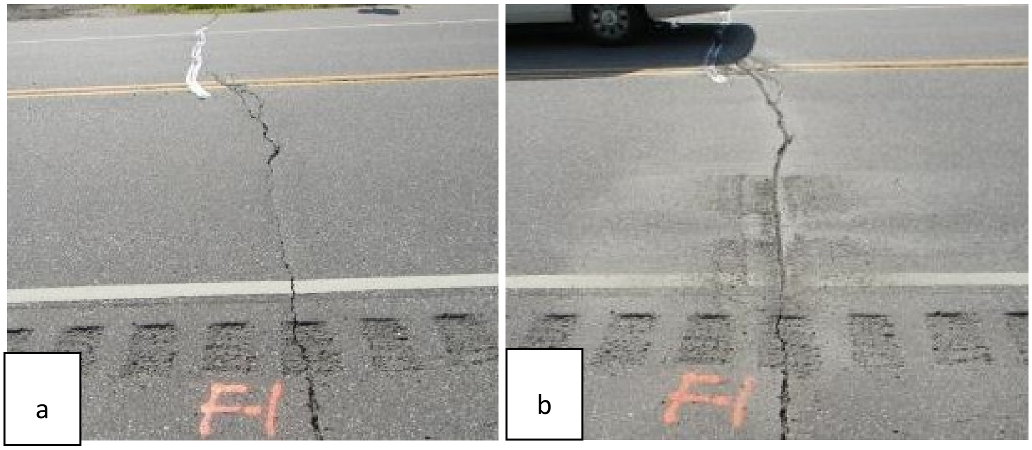


Figure 2.15: Crack (a) Before and (b) After Being Routed

Upon a crack being routed, air blasters, air lances, or wire rushes must be used to clean the crack prior to application of sealant. Figure 2.16 shows a routed crack after being air blasted and heat lanced.

Figure 2.16: Routed Crack After Cleaning

2.6.2.3 Sealant Preparation

Sealant preparation procedures for clean-and-seal and rout-and-seal are the same, except different grades of sealant are recommended in these.

2.6.2.4 Sealant Placement and Finishing

After being cleaned, a routed crack is ready to be sealed. For a rout-and-seal, two passes of sealant applications are made, typically with two different trucks about 5-10 minutes apart. The first pass fills the reservoir partially full with sealant. The sealant is allowed to seep into the crack as it cools. The second pass fills the reservoir full and finishes the placement in a band-aid, overband, or other configuration. Configurations are discussed in section 4.4 of this report. The reason that rout-and-seal is done in two passes is to allow the finished reservoir to lie flush with the surface of the pavement. Figure 2.17 (a) and (b) below show a routed crack after the first pass of sealant and after the second pass with blotter paper. A schematic of the cross-section view of the rout-and-seal sealant application is shown in Figure 2.18.

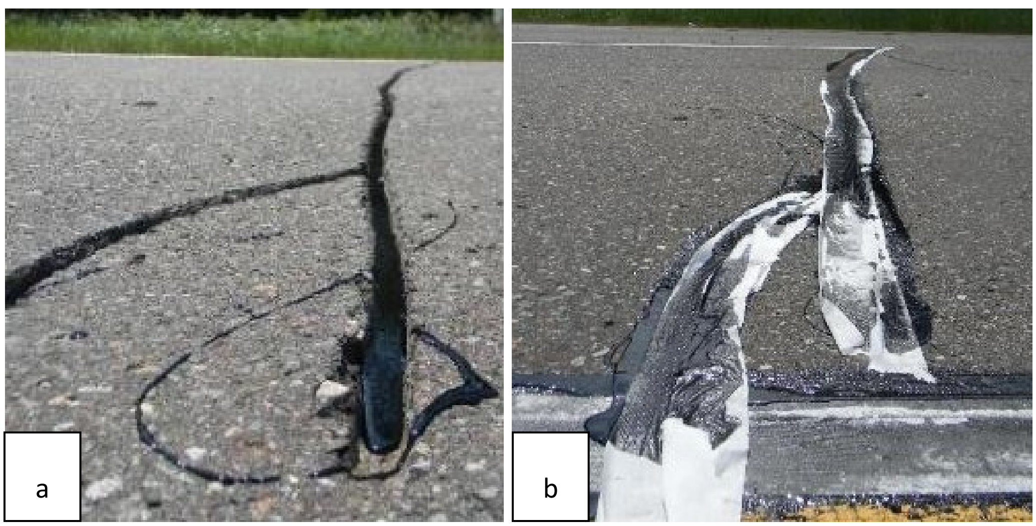


Figure 2.17: Routed Crack (a) After First Sealant Pass and (b) After Second Pass and Blotter Application

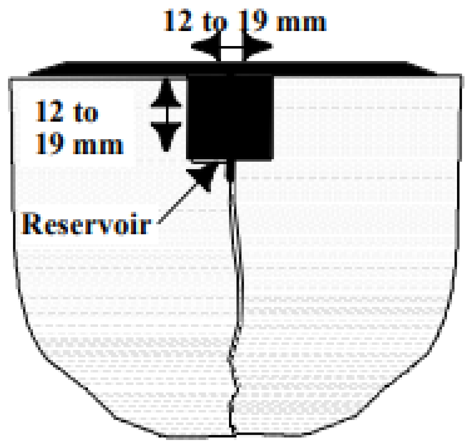


Figure 2.18: MnDOT Recommended Placement Configuration for Rout-and-Seal (after, Smith and Romine, 1999)

2.6.2.5 Labor Needs and Costs

The costs involved with rout-and-seal are much higher than those of clean-and-seal, largely due to increased labor needs. Rout-and-seal requires extra workers to operate the routing machines. Extra labor is also needed to operate the truck preforming the second pass of sealant into the routed reservoirs. There is also a cost increase because rout-and-seal requires more sealant material to fill the reservoirs. Johnson (2000) specified the unit price of a typical rout-and-seal to range between $0.50 and $0.85 per linear foot, depending on the size of the project; this is approximately two to three times more than what is required for clean-and-seal method.

2.7 PLACEMENT CONFIGURATIONS

With the chosen crack sealing method, the sealant can be finished in a variety of configurations. The Smith and Romine (1999) defined the most common configurations as shown below; also Figure 2.19 shows schematic of different sealant configurations.

Flush Fill: In this configuration, the material is simply placed into the existing crack. Excess material is scraped off.

Simple Band-aid: Material is placed into an uncut crack. The excess material over the crack is shaped into a flat overband using a squeegee.

Capped: Material is placed into an uncut crack. The excess material is left unshaped to form a “cap”.

Standard Reservoir-and-flush: Material is poured into a routed crack. No excess material is placed outside of the reservoir.

Standard Recessed Band-aid: Material is poured into a routed crack. Excess material is shaped into a thin overband using a squeegee.

Deep Reservoir-and-flush: Material is poured into a deep reservoir with no overband configuration.

Deep Recessed Band-aid: Material is poured into a deep reservoir and the excess material is shaped into a thin overband with a squeegee.

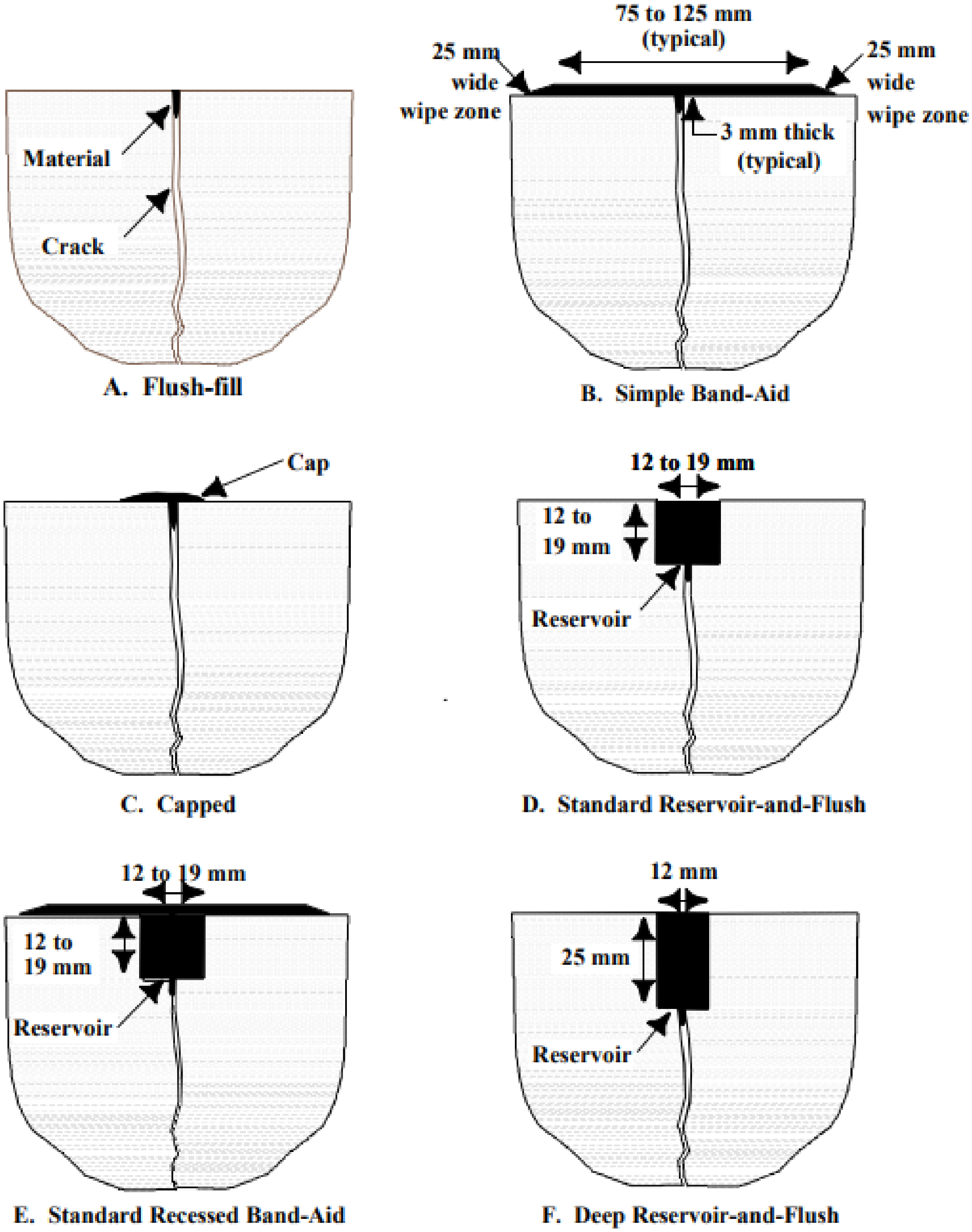
Shallow Reservoir-and-Flush: Sealant is poured into a wide reservoir with no excess material.

Shallow Recessed Band-Aid: Material is poured into a wide reservoir and finished with a thin overband using a squeegee.

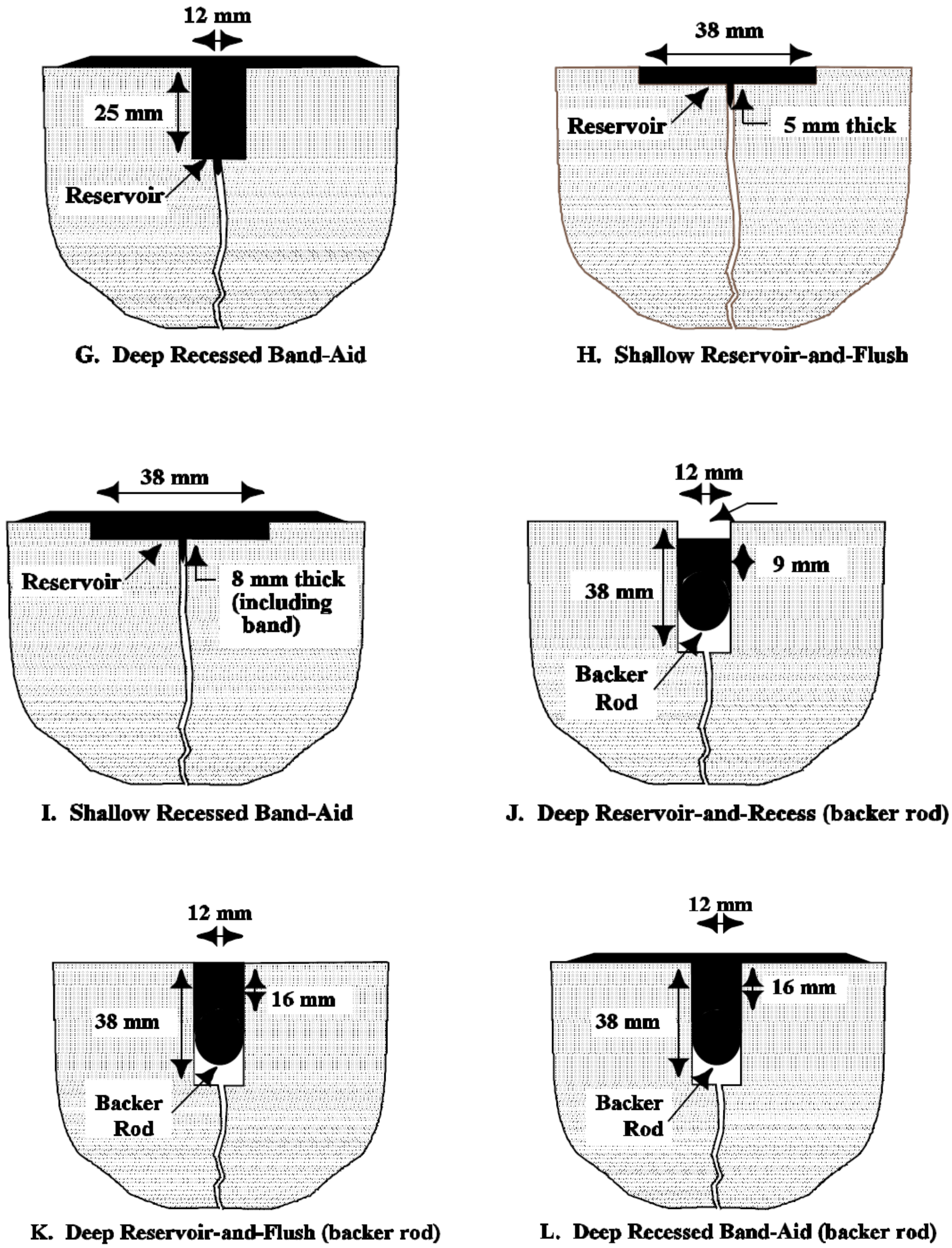
Deep Reservoir and Recess (Backer Rod)*:* A backer rod is installed into the bottom of the reservoir to keep sealant from flowing into the crack or from forming a bond with the bottom of the reservoir. The reservoir is then partially filled with sealant. No sealant is brought to the surface, in order to prevent material from sticking to tires.

Deep Reservoir-and-Flush (Backer Rod): Material is poured onto a backer rod that is paced into the bottom of a deep reservoir. No excess material is placed outside of the reservoir.

Deep Recessed Band-Aid (Backer Rod): Material is poured onto a backer rod placed at the bottom of a reservoir. The material is then finished with a thin overband at the surface using a squeegee.


Material
Crack
A. Flush-fill
75 to 125 mm
(typical)
25 mm
wide
wipe zone
25 mm
wide
wipe zone
3 mm thick
(typical)
B. Simple Band-Aid
Cap
C. Capped
12 to 19 mm
12 to
19 mm
Reservoir
D. Standard Reservoir-and-Flush
12 to 19 mm
12 to
19 mm
Reservoir
E. Standard Recessed Band-Aid
12 mm
25 mm
Reservoir
F. Deep Reservoir-and-Flush

(i)



(ii)

Figure 2.19 (i) and (ii): Various Sealant Configurations (after, Smith and Romine, 1999)

2.8 TYPES OF SEALANTS USED IN MINNESOTA

The type of sealant is a factor of climatic conditions, crack properties (spacing, density, and orientation), traffic loading, and material availability with respect to cost. The most significant properties for a crack sealant material to poses are:

a. Durability – The ability to endure traffic loading, tire wear, and climatic variations.
b. Extensibility – The ability of the material to deform as a crack expands.
c. Resilience – The ability of the material to recover after deformation.
d. Adhesiveness – The ability for a material to create a good bond to the wall of a crack.
e. Cohesiveness – The ability for a sealant to not suffer from internal ruptures during elongation.

The different types of materials used to seal and fill cracks can be categorized into three types:

1) Cold-applied thermoplastic bituminous materials
    a. Liquid asphalt (emulsion)
    b. Polymer-modified liquid asphalt
2) Hot-applied thermoplastic bituminous materials
    a. Asphalt cement
    b. Fiberized asphalt
    c. Rubberized/Polymerized asphalt
    d. Asphalt rubber
    e. Low-modulus rubberized or polymerized asphalt
3) Chemically cured thermosetting materials
    a. Self-leveling silicone

Typically, cold-applied thermoplastics and low-quality hot-applied thermoplastics are used for filling procedures. Higher quality hot-applied thermoplastics and silicone materials are used for sealing operations. As per ASTM D 6690 (2015), rubber and polymer-modified sealants are categorized into four classes to match low-temperature performance with climate, as shown below:

Type I: Moderate Climates, 50% extension at 0^{o}F

Type II: Most climates, 50% extension at -20^{o}F

Type III: Most climates, 50% extension at -20^{o}F, with other special tests

Type IV: Very cold climates, 200% extension at -20^{o}F

Various state agencies have made modifications to the ASTM D 6690 specifications to better suit their climatic and traffic conditions. Al-Quadi et al. (2017) developed performance-based test guidelines for selecting hot-applied thermoplastic sealants. In that study, a new set of testing regulations for sealant properties was developed and recommended as various provisional AASHTO standards, as provided in Appendix A.

The Minnesota Department of Transportation (MnDOT) uses three categories of sealants as provided below:

1) MnDOT 3719
2) MnDOT 3723
3) MnDOT 3725

The MnDOT specifications have additional requirements on top of the in-place ASTM D 6690 specification. When compared to various other state transportation departments, these specifications are much more precise. The physical requirements of these specifications, as defined by the 2016 Minnesota Standard Specifications for Construction (MnDOT, 2016), are provided in appendix A.

2.8.1 MnDOT 3719 (Joint and Crack Sealer: Hot-Poured, Crumb Rubber Type)

MnDOT 3719 is recommended for crack filling of non-working transverse and longitudinal cracks. The test specification requires that the sealant material be composed of a mix of asphalt and crumb rubber that is blended into a homogeneous mixture. The sealant is required to be heated in a double-walled melter with mixing and temperature monitoring.

2.8.2 MnDOT 3723 (Joint and Crack Sealer: Hot-Poured, Elastic Type)

MnDOT 3723 exhibits good adhesion qualities and is recommended to be used in clean-and-seal and rout-and-seal, where wider reservoirs are needed. The specification requires a sealant to be composed of a combination of polymeric materials, fully reacted chemically to form a homogenous compound.

2.8.3 MnDOT 3725 (Joint and Crack Sealer: Hot-Poured, Extra Low Modulus, Elastic Type)

MnDOT 3725 has low resilience properties and is recommended only for use in transverse rout-and-seal applications. As with MnDOT 3723, this specification requires that sealant be composed of a homogenous mixture of fully chemically reacted polymeric materials. The heating of the material shall take place in a temperature regulated, double-walled tank with mixing.

CHAPTER 3: PREVIOUS STUDIES ON CRACK SEAL PERFORMANCE AND BENEFITS

3.1 PERFORMANCE EVALUATION OF CRACK SEALS

Smith and Romine (1999) suggested that sealant performance can be measured by summing the lengths of failed segments and dividing by the total length of treated cracks inspected. After multiple field inspections, a graph can be made that shows the treatment effectiveness over time. Also, by defining a minimum threshold of effectiveness, the project lifespan can be determined. Figure 3.1 shows such a graph, with treatment effectiveness (%) on the y-axis and age (months) on the x-axis. In addition, the author recommended that at least one inspection be performed each year on treated cracks to document the failure rates and plan for future maintenance operations. It is also recommended that a mid-winter evaluation shall be conducted in order to evaluate the performance of crack treatments during maximum crack expansions. Caltrans (2008) provided a guideline on the crack sealant distresses and their likely cause and remedial measures. See Table 1 and Table 2.

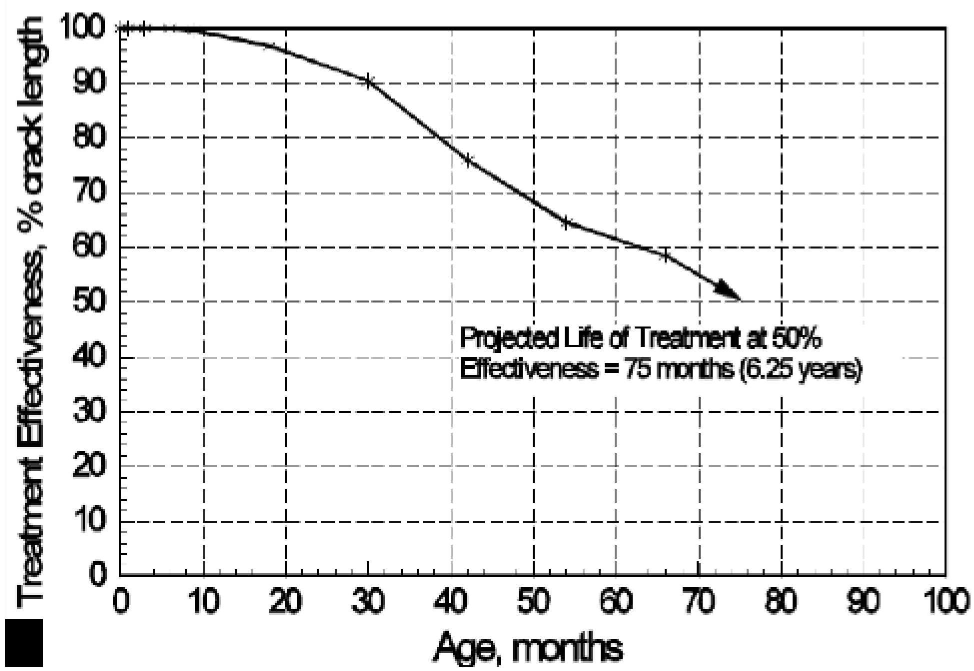


Figure 3.1: Trend of Seal Deterioration over Time (after, Smith and Romine, 1999)

Table 1: Possible Sealant Failures and Likely Causes (after Caltrans, 2008)

CAUSE	PROBLEM						
	ALL SEALS			EMULSION SEALS ONLY			
	Tacky Picks Up	Re-Cracks Quickly	Bumpy Surface	Separation From Crack Sides	Emulsion Sealer Not Breaking	Emulsion Sealer Breaks Too Fast	Emulsion Sealer Washes Off
Crack Wet					●		●
Sealant Not Cured	●			●		●	
Crack Dirty	●	●		●		●	
Insufficient Sanding	●			●		●	
Poor Finish, Wrong Tools	●	●	●	●		●	
Sealant Too Cold		●	●				
Sealant Too Hot	●			●			
Application Too High	●		●	●			
Application Too Low		●	●				
Sealant Degraded Due to Overheating	●	●	●	●	●	●	●
Rain During Application					●		●
Cold Weather		●			●		
Hot Weather	●		●	●		●	

Table 2: List of Solutions for Commonly Observed Sealant Failures (after Caltrans, 2008)

Problem	Solution
Tracking	• Reduce the amount of sealant or filler being applied. • For hot applied materials, allow to cool or use sand or other blotter. • Allow sufficient time for emulsions to cure or use a sufficient amount of sand for a blotter coat. • Ensure the sealer/filler is appropriate for the climate in which it is being placed.
Pick out of Sealer	• Ensure cracks are clean and dry. • Increase temperature of application. • Use the correct sealant for the climate. • Allow longer cure time before trafficking.
Bumps	• Check squeegee and ensure it is leaving the correct flush finish. • Have squeegee follow more closely to the application. • Decrease the viscosity of the sealer. • Change the rubber on the squeegee. • Stop using overbanding.

Al-Quadi et al. (2017) described the most common types of distresses (Figure 3.2) observed in crack sealants as follows:

(a) Adhesion loss – the loss of bond between the sealant and sidewall of the crack.
(b) Cohesion loss – the loss of bond within the sealant material itself.
(c) Overband wear – the loss of overband material to tires and snowplows.
(d) Tracking – the pull-out of material by vehicle tires and snowplows.
(e) Stone intrusion – the intrusion of rocks into the seal.

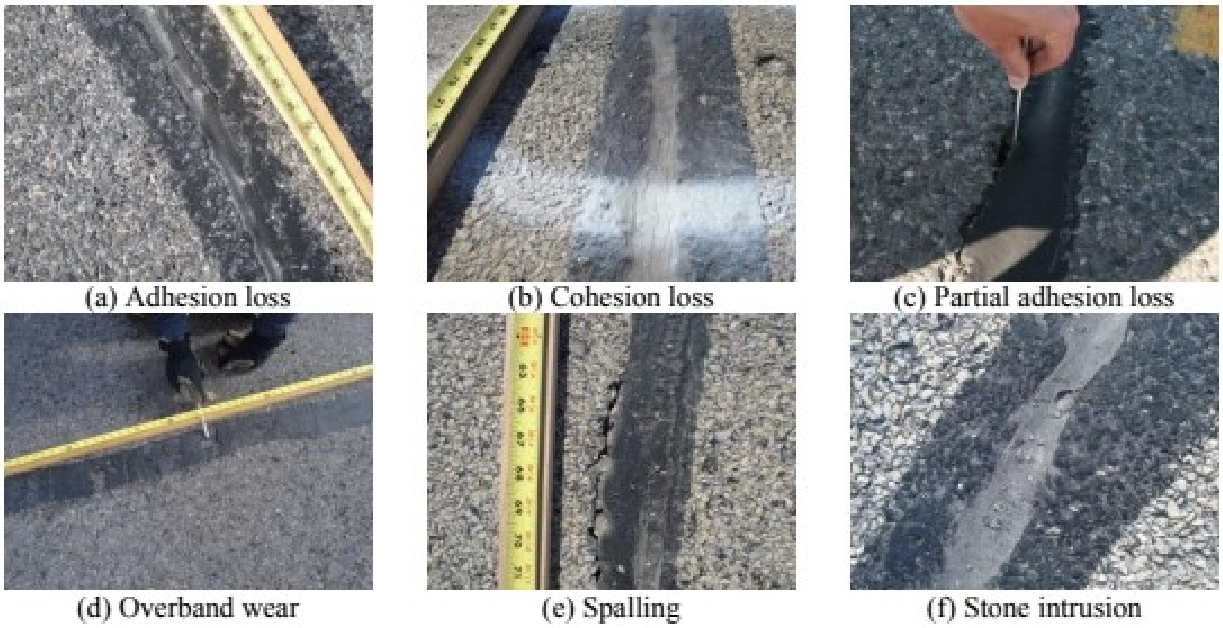
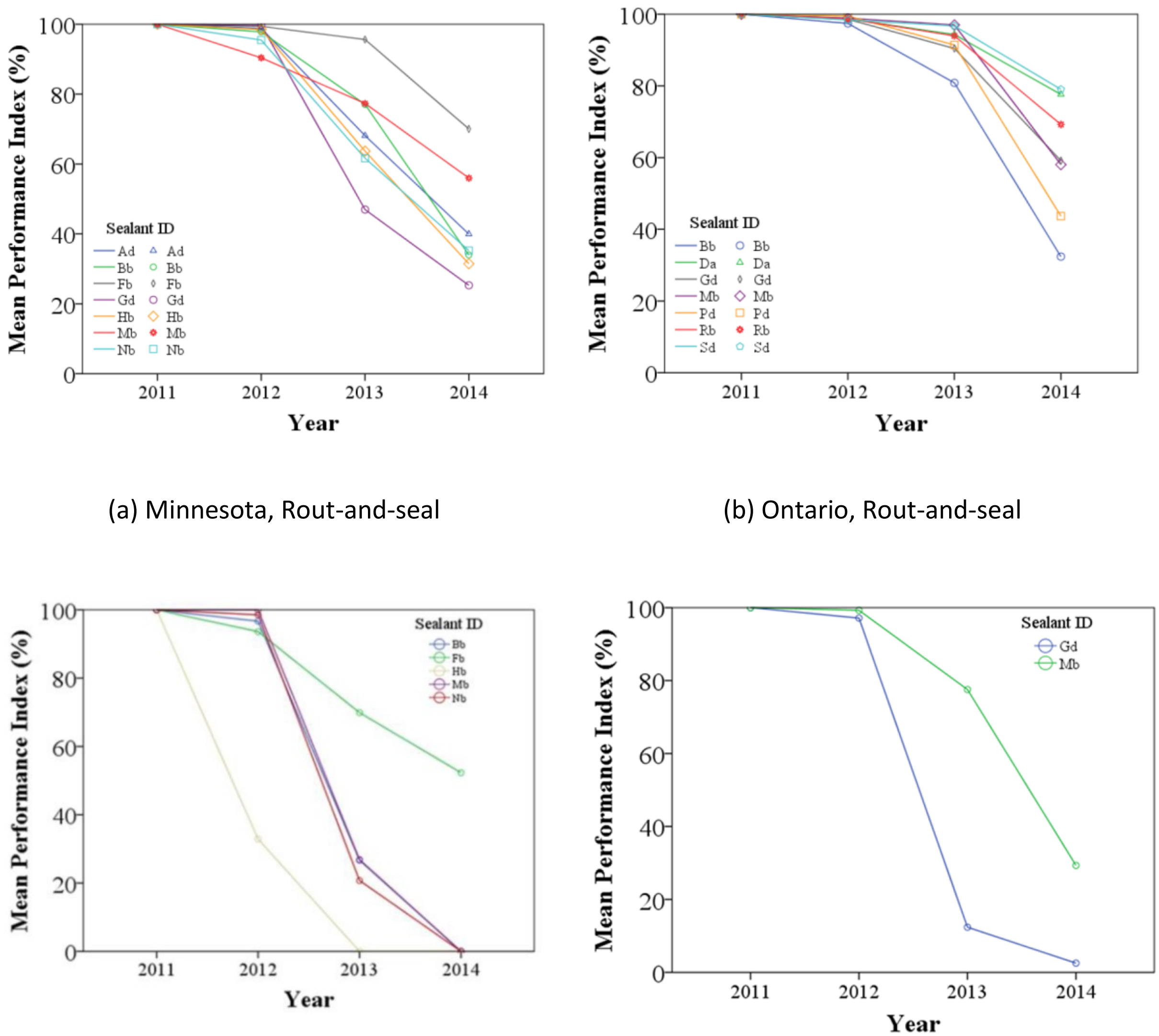


Figure 3.2: Various Sealant Failures (after, Al Quadi, 2017)

Performance of more than 200 cracks was evaluated and documented. Representative pavements from several states (including Minnesota) and a couple of provinces of Canada were considered in the study. Each crack was evaluated for percentage length of full-depth adhesive and cohesive failures, plus the percentage length of partial-depth adhesive and cohesive failures. Percent length of overband wear, percent length of spalling, and the amount of stone intrusion were also documented. Sealant performance was used to determine the performance index (PI). The performance index is a function of percent full-depth adhesive loss and cohesive failures (AC) and a percent of partial adhesive and cohesive failures (PAC) as shown in Equation 1.

$$PI = 100 - (AC + PAC \times 0.5) \qquad (1)$$

It was observed that the most common failure was the adhesion loss that occurred during the winter months. The performance of various sealant and seal types was monitored over three years. Figure 3.3 shows typical examples of performance evaluations for Minnesota and Ontario (Canada) sites of rout-and-seal and clean-and-seal for various sealants. It can be seen that the significant drop in PI values for a majority of the seals occurred between the second and third winters. The clean-and-seal almost completely failed in all sections after the second winter, where rout-and-seal was still performing with an acceptable threshold. The exact performance indexes are listed in Figure 3.4.



(a) Minnesota, Rout-and-seal

(b) Ontario, Rout-and-seal

(c) Minnesota, Clean-and-seal

(d) Ontario, Clean-and-seal

Figure 3.3: Performance Evaluations of Crack Seals and Sealants (after Al-Quadi et al., 2017)

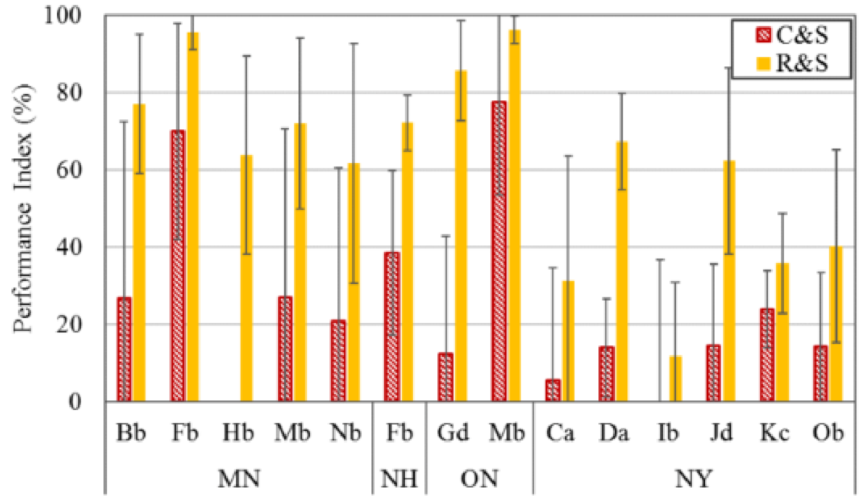


Figure 3.4: Performance Indices of Clean-and-seal (C&S) and Rout-and-seal (R&S) Methods (after Al-Quadi et al., 2017)

In that study, in order to observe the influence of the overband, two roadway sections in New York (NY) and New Hampshire (NH), were used; both overband and no-overband placement configurations of sealant were also considered. As shown in Figure 3.5, it was found that the overband seals out-performed the no-overband seals for all sealant types in most cases.

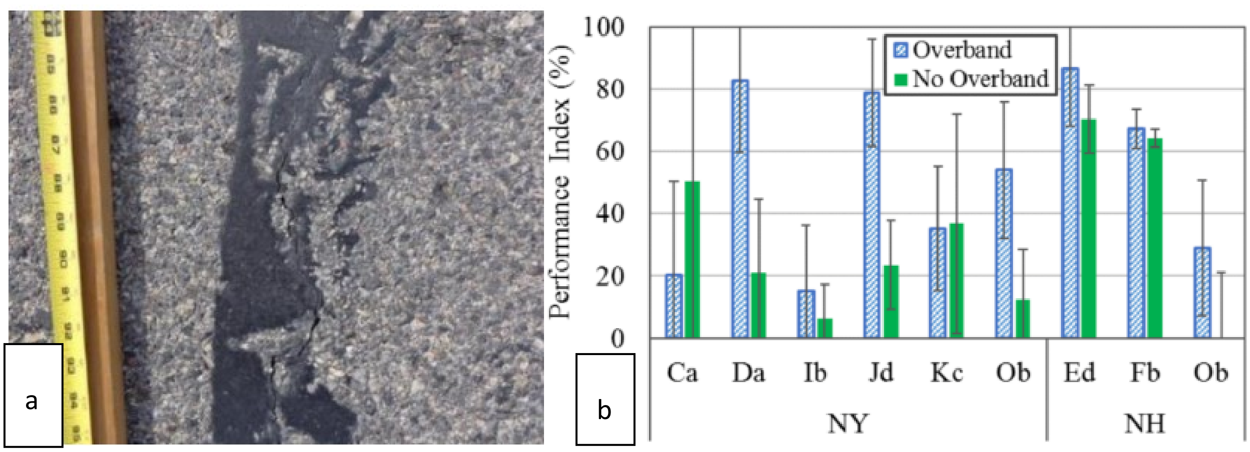


Figure 3.5: (a) Overband Failure and (b) PI Comparison of Overband vs no-overband seals (after, Al-Quadi et al., 2017)

Al-Quadi et al. (2017) also studied the effects of plow damage on clean-and-seal overbands in a roadway at Michigan. The performance index of seals was evaluated over a three year time period. The Performance Index (PI) was computed using the percent overband failure (OBF) caused by plow abrasion and sealant tracking, as shown in Equation 2.

$$PI = 100 - \%OBF \qquad (2)$$

It was found that the sealant suffered little damage in the first couple of years; however, there was a great reduction in PI from 2012 to 2013.

3.2 BENEFIT OF CRACK SEALING

Rajagopal (2011) performed a study in cooperation with the Ohio Department of Transportation (ODOT) to determine the overall benefit of crack sealing. The questions that the study addressed were:

- Do existing crack sealing practices within ODOT enhance pavement performance?
- If so, what is the optimum timing for treatment?
- Does the crack seal extend pavement life?
- Does crack sealing provide cost benefit? If so, to what extent?

Performance of several crack seals, mostly sealed with clean-and-seal technique, was evaluated at different times to understand the overall benefits of crack sealing. Different types of pavements were considered in that study as shown in Table 3. Service lives of the control sections (not sealed) were compared with the sections that were sealed. It can be seen in Table 3 that creak seal could extend the life of the pavement irrespective of the type of pavements. This study also found out that crack sealing can enhance a pavement condition rating (PCR) by 5 points. The other significant observation in that study was that the clean-and-seal could provide the largest five-year condition gain when the sealing is performed in pavements with a PCR of 66 to 80. Operating outside of this range produced lower condition gains.

Table 3: Service Life Extension among Various Pavement Types (after, Rajagopal, 2011)

	Threshold PCR=60			Threshold PCR=65		
	All Pavements	**Composite Pavements**	**Flexible Pavements**	**All Pavements**	**Composite Pavements**	**Flexible Pavements**
Life of Crack sealed Subsections	4.87	7.70	3.14	3.25	5.82	1.81
Life of Control Subsections	3.79	7.46	2.09	1.56	4.55	0.29
Extension of Service Life, years	1.08	0.23	1.06	1.69	1.27	1.52

In another study, Hajj et al. (2010) evaluated the performance of various maintenance activities including crack filling by determining the Present Serviceability Index (PSI) before and after the treatment until failure. A benefit-cost ratio analysis was used to compare the performance of various test sections and corresponding treatments. The benefit was measured in terms of area under the performance curve plotted between PSI and Time in years. The cost per lane-mile included the cost of labor, material, and equipment. This study determined that crack filling is beneficial when performed on pavements that have a present serviceability index (PSI) of 2.5 or more.

CHAPTER 4: CRACK SEAL PERFORMANCE EVALUATION IN PRESENT STUDY

Crack sealing performance data was collected from multiple sources as shown in Figure 4.1. Since data from these sources were collected at different times and scenarios, they were categorized as Phase 1, 2, 3, and 4.

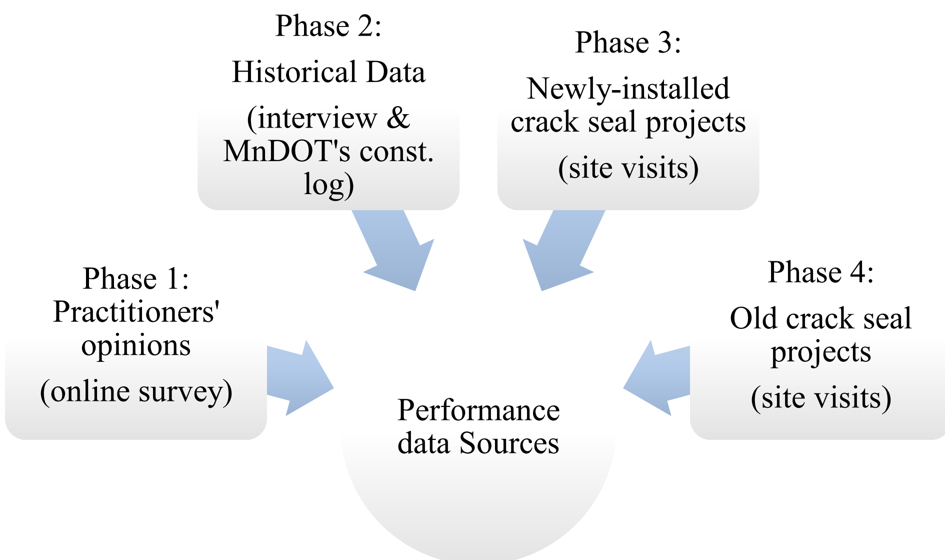


Figure 4.1: Crack Sealing Performance Data Sources

4.1 PHASE 1: PRACTITIONERS' OPINIONS (ONLINE SURVEY)

The objective of the online survey was to understand the current practice of crack sealing methods in the state of Minnesota and to generate a group of practitioners to collect more site-specific data. A short five-question survey form was distributed to collect information on (i) the most commonly used crack sealing method, (ii) criteria followed for deciding the suitable method, and (iii) average anticipated service life for different sealing methods. The online survey was conducted electronically using 'Google Survey Form' during the summer of 2017. A copy of the survey form is provided in Appendix B. The participants of the online survey were state-aid engineers, and personnel from MnDOT districts, counties, and cities.

A total of 47 practitioners from various parts of the state participated in this short survey. The locations of these responders are provided in Table 4. A map of the locations of the responders is shown in Figure 4.2; where yellow, red, and green pins indicate city offices, county offices, and MnDOT districts that responded, respectively.

Table 4: List of MnDOT Districts, Counties, Cities, and Contractors that participated in the Online Survey.

County Offices	Cities	MnDOT Districts
1. Lincoln County	1. Albert Lea	
2. Clay County	2. Burnsville	
3. Pennington County	3. St. Michael	1. MnDOT District 7
4. Dodge County	4. Inver Grove Heights	2. MnDOT District 6
5. Sherburne County	5. Coon Rapids	3. MnDOT Metro
6. Hennepin County	6. Austin	4. MnDOT District 8
7. Cottonwood County	7. Crystal	
8. Houston County	8. Rosemount	
9. Wabash County	9. Shoreview	
10. Clearwater County	10. Little falls	
11. Mille Lacs County	11. Hutchinson	
12. Fillmore County	12. Pipestone	
13. Aitkin County	13. Mankato	
14. Murray County	14. Redwing	
15. Anoka County	15. Bemidji	
16. Koochiching County	16. Woodbury	**Private Contractors**
17. McLeod County	17. Andover	
18. Rice County	18. Roseville	1. WSB & Associates
19. Sibley County	19. Oakdale	
20. Blue Earth County	20. West St. Paul	
21. Pope County		
22. Ottertail County		

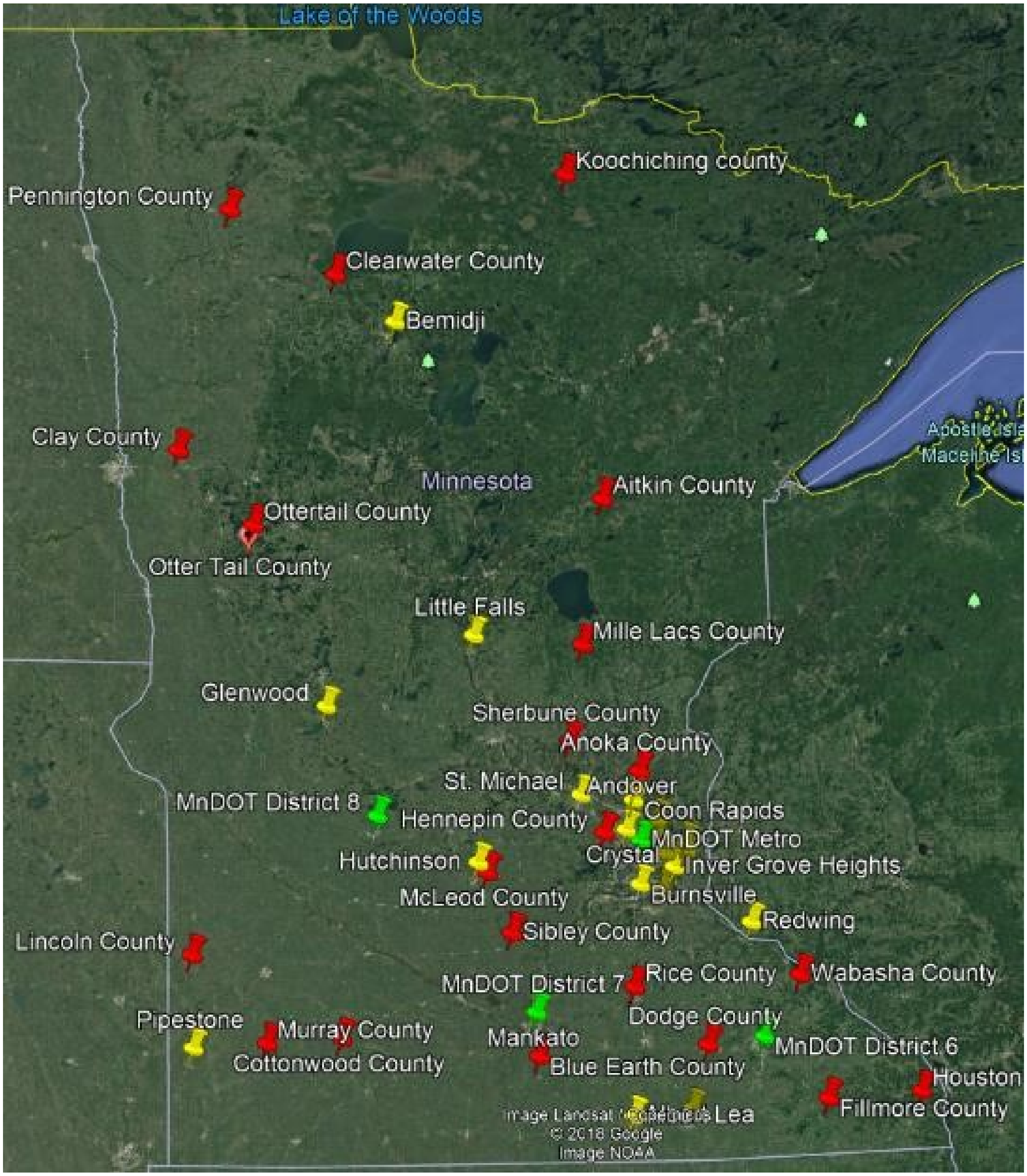


Figure 4.2: Locations of the Online Survey Responders (Cities: Yellow, Counties: Red, MnDOT Districts: Green)

4.1.1 Data Analysis

Question 1: The first question was aimed at determining the most commonly used crack sealing method in Minnesota. Figure 4.3 and Figure 4.4 analyze responses for Question 1 in the form of pie-charts. Figure 4.3 shows all the data; whereas, Figure 4.4 shows the data broken into categories by agency type (city, county office, and MnDOT district). Figure 4.4(a) and Figure 4.4(b) show that counties and cities mostly use the rout-and-seal method. The pie chart in Figure 4.4(c) shows that out of the four MnDOT districts participated in the survey; three districts mostly prefer clean-and-seal method over the more expensive rout-and-seal method. However, since only four districts participated in the survey, it may not be appropriate to generalize the preference for all the MnDOT districts. Figure 4.5 shows the geographic locations of the responders according to their preference of sealing method: yellow pins indicate locations that reported the primary use of rout-and-seal and green pins indicate the locations that reported the primary use of clean-and-seal. No clear trend is seen by locating geographic positions, however.

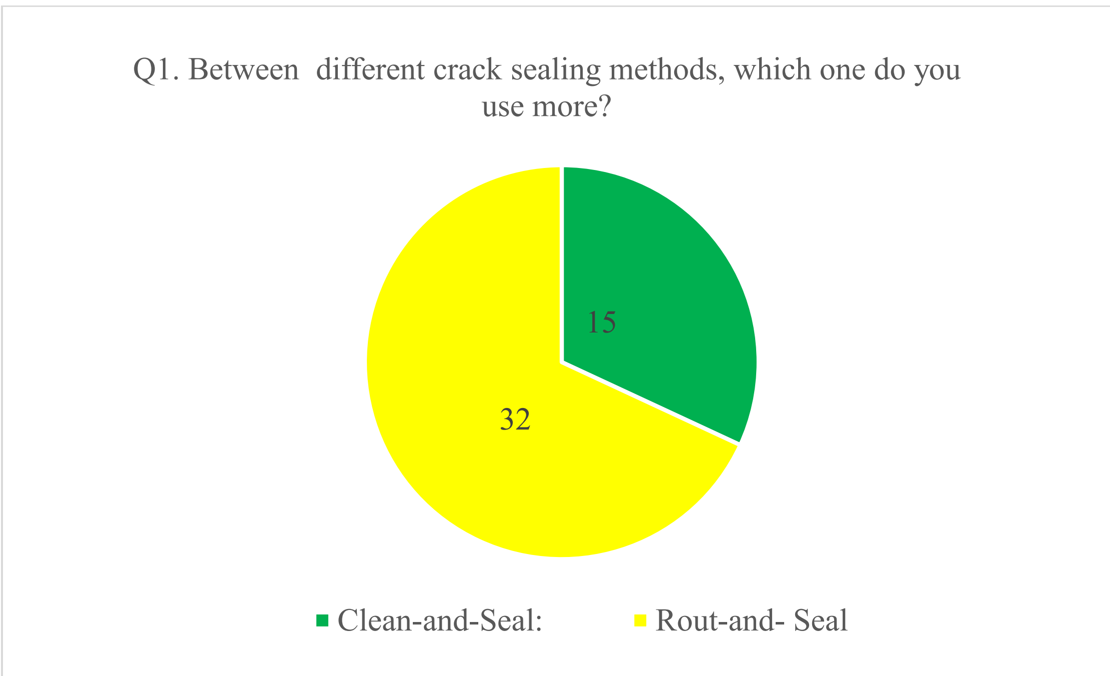


Figure 4.3: Analysis of the Responses to Question 1, All data

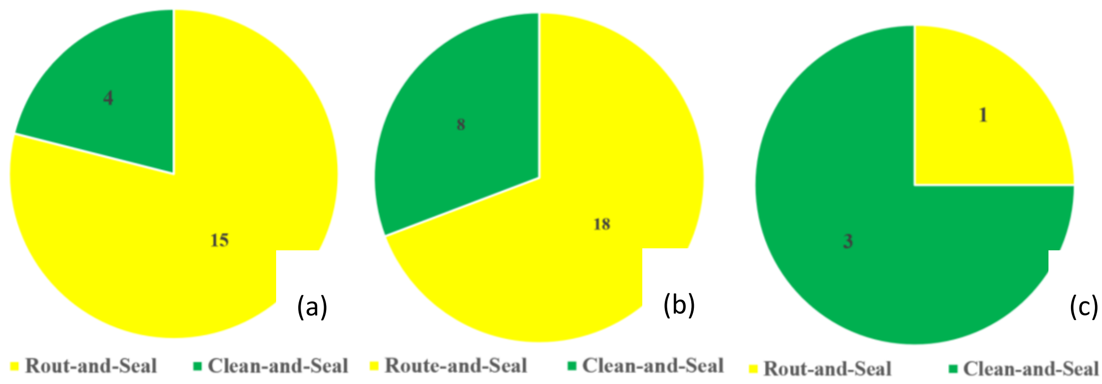


Figure 4.4: Preferred Crack Sealing Method (a) City Offices (b) County Offices (c) MnDOT Offices

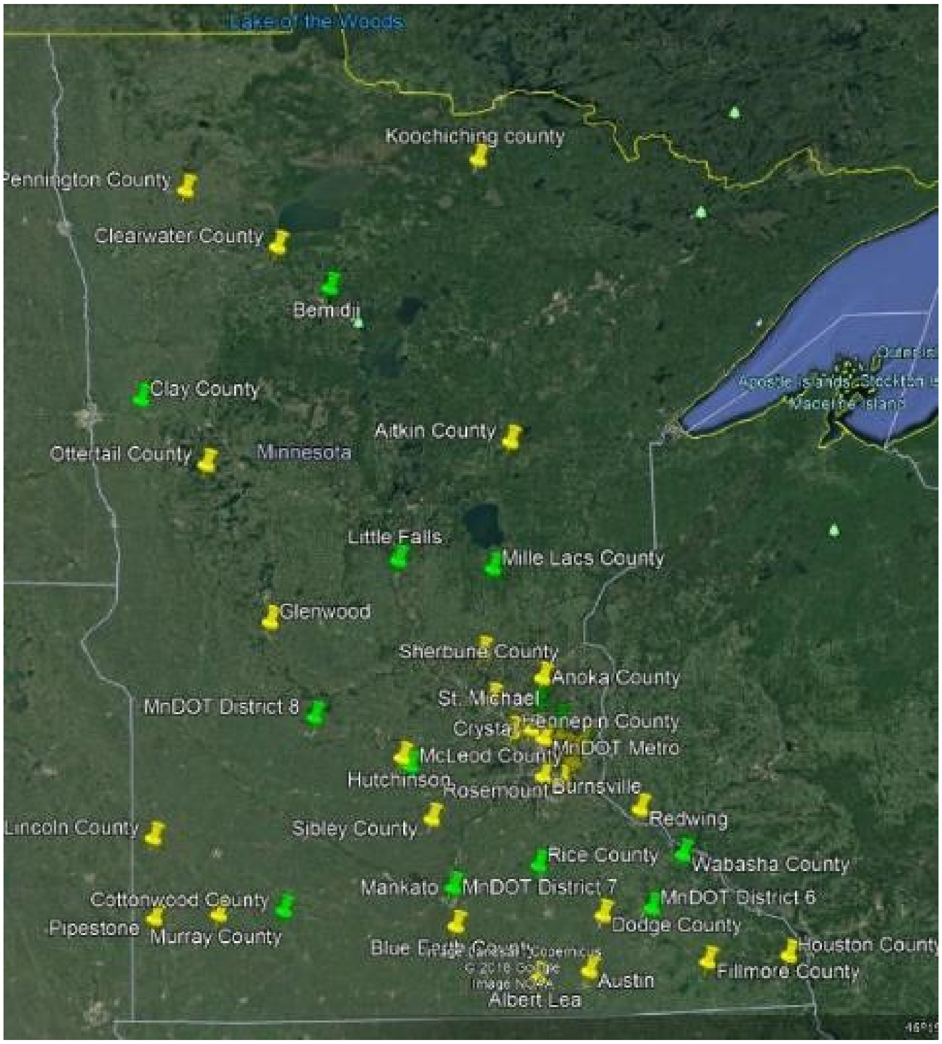


Figure 4.5: Locations Reporting Preference about the Crack Sealing Method: Rout-and-seal (yellow) and Clean-and-seal (green)

Question 2: This question was asked to understand the selection criteria for choosing a crack sealing method. Figure 4.6 analyzes the responses obtained for this question. Although responses were varied, an effort was made to compile the results into different categories. The categories include no criteria, pre-determined schedule, crack/pavement conditions, pavement age, subgrade material, and budget. It can be seen that the most common criteria for selecting the crack sealing method are the crack/pavement conditions, some practitioners although use the pre-determined schedule and pavement age as the criteria for choosing the sealing method.

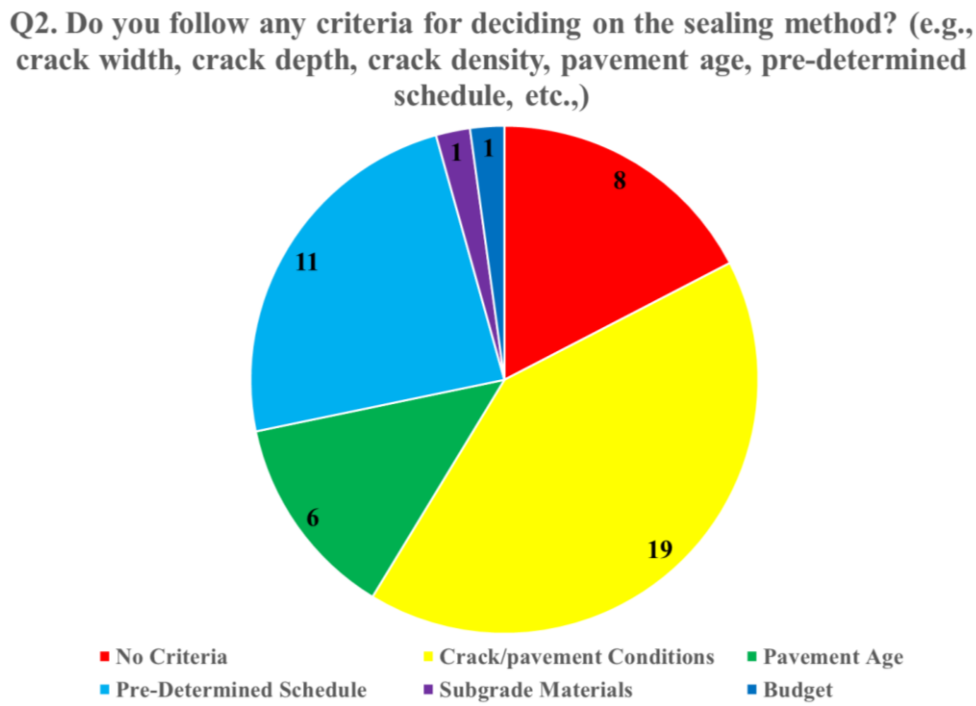


Figure 4.6: Analysis of the Responses to Question 2

When responses from questions 1 and 2 were combined, it was observed that those who primarily use rout-and-seal method, a good number (6 out of 31) of them do not follow any criteria (Figure 4.7). The responders who answered that they primarily use clean-and-seal method indicated that they most typically use crack conditions as their method selection criteria (Figure 4.8).

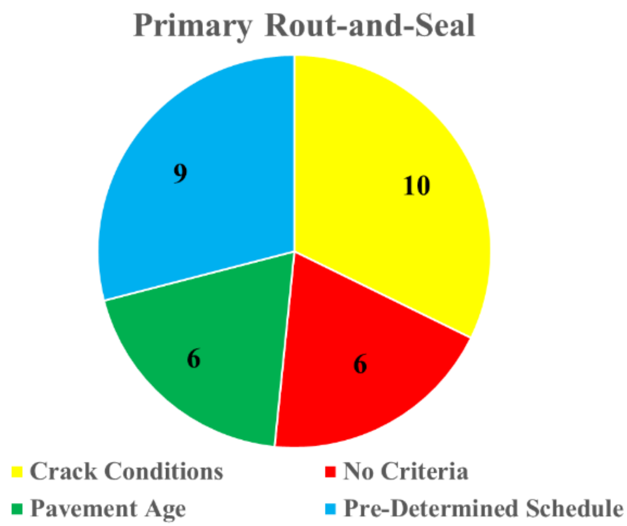


Figure 4.7: Selection Criteria for Rout-and-seal

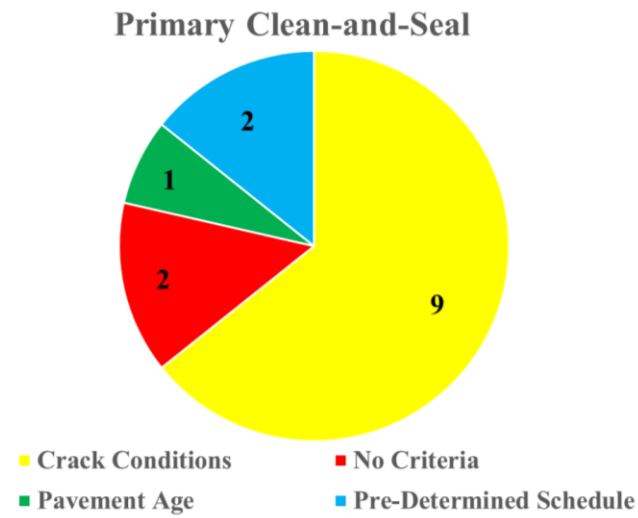


Figure 4.8: Selection Criteria for Clean-and-seal

Question 3: This question was asked to know the typical service life of the seal when installed according to the clean-and-seal method. The service life is defined as the time between the sealant installation and failure. Since several responders noted that they only use the rout-and-seal method, the response was not provided to this question by all the 47 responders. Available responses were grouped into several ranges and presented in Figure 4.9. These responses were ranged from 2-3 years to over a10-year period. Note that the variability in the responses could be because no threshold serviceability was defined in the question. Additionally, some of the responders may not track the performance of crack sealing closely enough to provide a quantitative assessment.

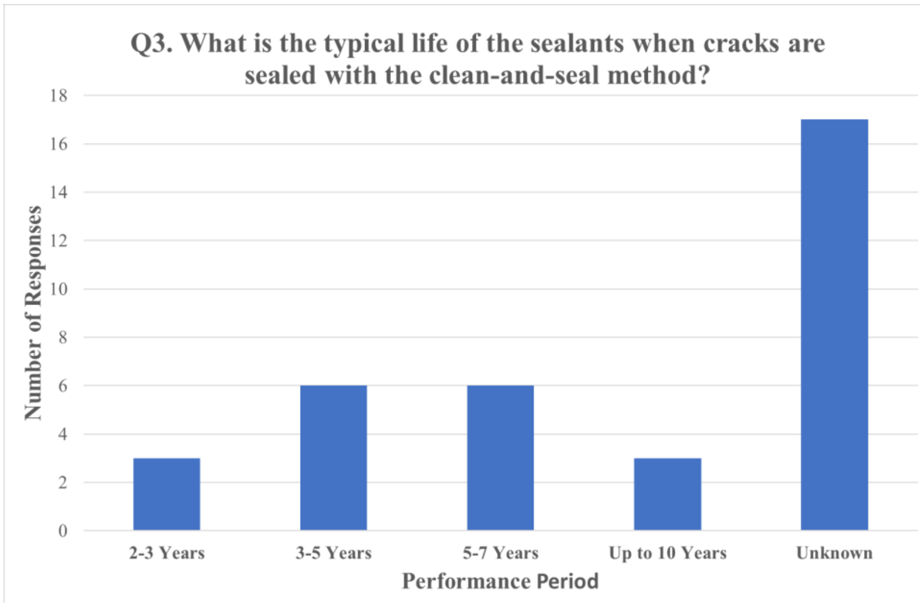


Figure 4.9: Typical Service Life of Clean-and-seal Method

Question 4: This question was asked to know the typical service life of seals installed using the rout-and-seal method. Responses were grouped into several ranges and presented in Figure 4.10. These responses ranged from 2-5 years to over 15 years. In addition to the reasons for variation in the service life mentioned in Question 3, the performance of the seals is likely influenced by the pavement and traffic conditions.

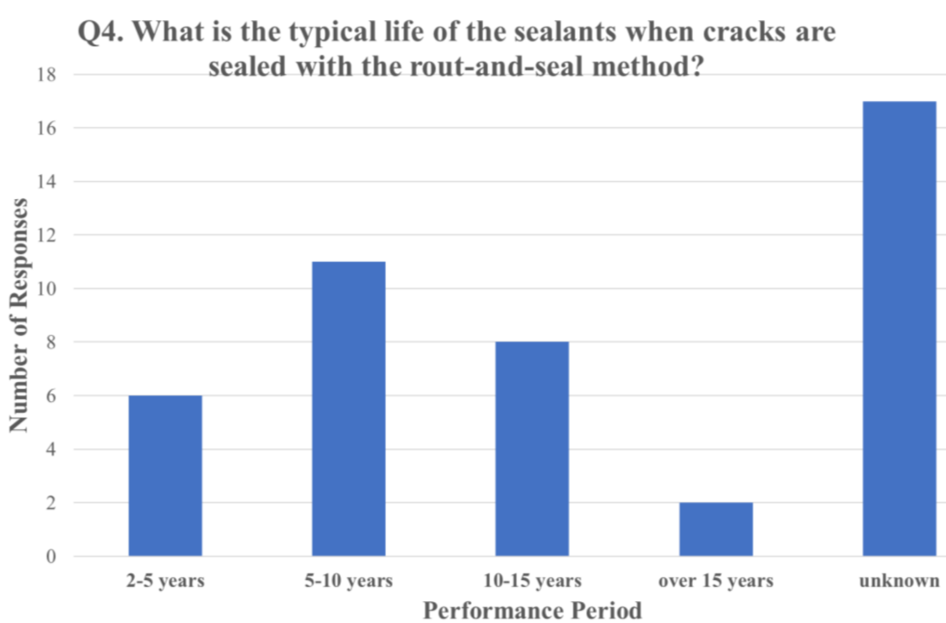


Figure 4.10: Typical Service Life of Rout-and-seal Method

Question 5: This question was asked to know if the responder would be willing to further participate in this study by providing site-specific information. A total of 24 responders agreed to provide additional information, as shown in Figure 4.11. From those 24 who responded "yes," a total of seven indicated that they primarily use clean-and-seal, while the remaining 17 reported the primary use of rout-and-seal (Figure 4.12). A follow-up, in-depth survey was sent to the 24 responders to obtain the performance data of previous crack sealing projects. The results of the follow-up survey are presented in section 4.2 of this report.

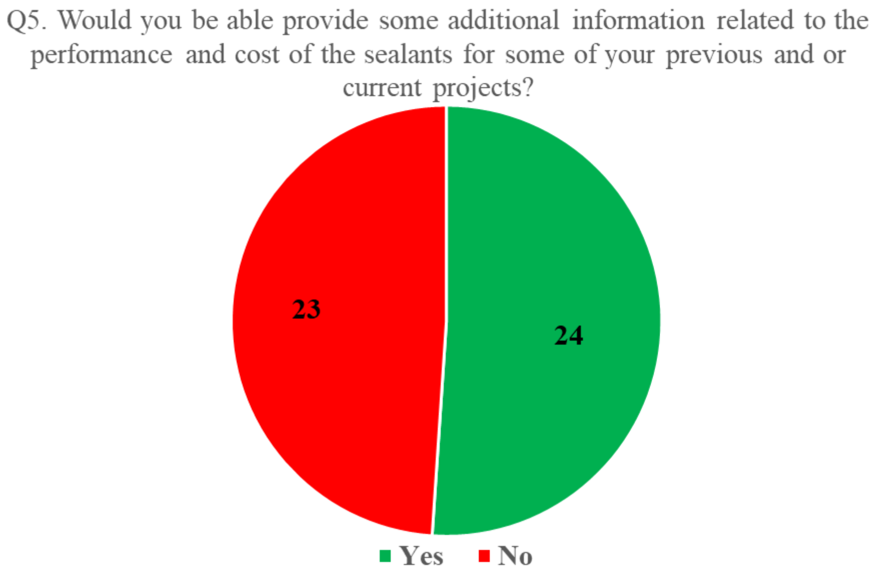


Figure 4.11: Number of Responders agreed to take the Follow-up Survey

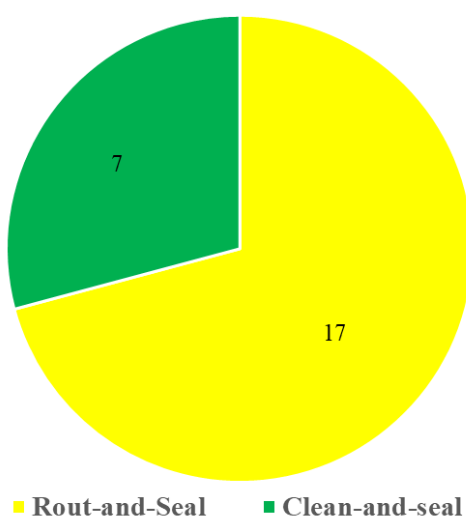


Figure 4.12: Preference of the Sealing Method for the Responders of Question 5

Question 6: The purpose of this question was to select some representative field sites for collecting crack seal performance data from newly sealed projects. A total of eleven project sites, located throughout the state, were identified where cracks were sealed in the Summer and Fall of 2017. The descriptions of these crack sealing project sites are presented in Section 4.

4.2 PHASE 2: HISTORICAL DATA

In order to collect more in-depth and site-specific data, a secondary survey form (Appendix C) was sent out to 24 survey participants those had previously agreed to provide additional information (Online survey: Q#5). This survey also asked questions on the cost-effectiveness of crack sealing methods. Even though good responses were received on the cost related questions from this exercise, conclusive information could not be collected on the crack seal performance. The research team then conducted telephonic or face-to-face interviews to determine alternate data sources. Based on the feedback of these interviews, it was understood that MnDOT's Pavement Construction Project Log could be a good source to estimate the service period of the crack seals. Accordingly, the historical data of crack sealing projects were collected and studied to draw a possible conclusion on the service period of the crack seal as a function of various parameters, such as traffic, pavement surface layer's thickness and age at the time of sealant installation, sealant material, and sealing procedure. It may be noted that the 'service period' is defined as the period between the sealant installation and the follow-up surface treatment or major rehabilitation work, irrespective of the failure of the sealant. The 'service period' is different from the 'service life'; it is the period between the sealant installation and time when the sealant fails, irrespective of the follow-up surface treatment or major rehabilitation work.

4.2.1 Interviews

A total of ten interviews were conducted, either through telephone or visiting the interviewee's work location; a majority of the people being interviewed were maintenance engineers or supervisors. The interviews were focused on collecting their experiences on the performance of the crack sealing methods and identifying potential data sources on the performance of the crack seals. The results of the interviews, however, did not yield a clear distinction between the performance of rout-and-seal and clean-and-seal methods in terms of their service life. MnDOT District 7 expressed that the clean-and-seal performs longer than the rout-and seal; according to them, the major drawback of the rout-and-seal is the adhesion failure. Whereas, MnDOT District 1, the City of Duluth, and the City of St. Michael prefer the rout-and-seal over the clean-and-seal method; the tearing out of sealant material is the notable failure with the clean-and-seal method according to them.

It was found that the deciding factors in choosing between rout-and-seal method and clean-and-seal method vary between the agencies. Some of the factors include the age of the pavement surface layer, crack width, and also the type of subgrade soil. For example, Sherburne County and the City of Andover use rout-and-seal on 1- to 2-year old asphalt layers and clean-and-seal on 8-year or older layers. Beltrami County uses rout-and-seal for pavements with clayey and silty soil subgrades and the clean-and-seal for sandy soil subgrades. The City of Hutchinson follows the crack width criteria as specified MnDOT guidelines. Many of these agencies also lay a seal coat on the crack-sealed sections in the same or following season, or a couple of years later, especially for the important roadways. At the same time, some agencies like Sherburne County and the City of St. Michael expressed their concerns with seal coat; they suspect seal coat invites moisture-related distresses, such as stripping.

From the interviews, it can be concluded that a greater number of agencies use rout-and-seal method than the clean-and-seal method. The choice of sealing method primarily depends on their experience and other local conditions. Overall, the interviews with the maintenance engineers or supervisors were helpful to recognize the current practice of crack sealing methods and most importantly identify another useful data source, such as MnDOT's Pavement Construction Project Log.

4.2.2 MnDOT's Pavement Construction Project Log

MnDOT maintains a record of pavement construction projects (MnDOT, 2018b) with details of year built, project number, type of work along with specification, thickness (if available), and plan of the project location. A screenshot of such data log is shown in Appendix D. Additionally, MnDOT maintains a traffic record (MnDOT 2018c) for various routes. A screenshot of traffic data for a county map is shown in Appendix D. MnDOT also maintains a record of post letting awarded bid abstracts (MnDOT 2018d) under Bid letting database. These abstracts provide the job description along with cost information. A screenshot of an awarded abstract search page from the bid-letting website is shown in Appendix D. Also, the data such as a list of crack sealing projects in last ten years, proposal documents, etc. were obtained from the MnDOT's Office of Materials and Research (Paul W. Nolan, Personal Communication). All of these data sources were initially used to identify the method of crack sealing performed and then to determine the service period.

4.2.2.1 Identification of Crack Sealing Methods

Rout-and-seal

In order to collect the performance of rout-and-seal projects, a total of 84 projects (Appendix E and Appendix F) were reviewed from various MnDOT districts. However, only 26 rout-and-seal projects were finally shortlisted based on the completeness of the dataset as shown in Appendix G and Appendix H. Note that many of the crack sealing treatments before the year 2000 were noted as crack repair; no documentation was found to identify the type of crack treatment though.

Clean-and-seal

Unlike the rout-and-seal method, it was difficult to identify the clean-and-seal projects from construction project log due to lack of information. Hence, the actual bid proposal documents for few potential projects (State Project # 8821-71/221/242, 8823-273, etc.), collected from MnDOT's Office of Material and Research, were used to identify the clean-and-seal projects. The proposals in which the sealant material Type 3723 was used, cracks were assumed to be sealed with the clean-and-seal method. Later, the construction plans (Appendix J) with details of project sites in those proposals were used to locate the project section.

A total of 12 clean-and-seal projects were identified (Appendix J and Appendix K), constructed between the year 2007 to the year 2013. These projects did not have any follow-up treatment on record. The latest available pavement condition ratings (MnDOT 2018e) performed in 2016 indicate that these project segments are still in good condition.

4.2.2.2 Traffic Data

MnDOT's traffic data maps that are available for different years were used to determine the representative Average Annual Daily Traffic (AADT) for each project section. This was obtained by averaging the traffic between the year of crack sealant installation and the year of follow-up treatment (Appendix L to Appendix N).

4.2.2.3 Service Period

The performance of crack seals was evaluated based on the average service period. Even though the service period may be influenced by the factors like AADT, thickness, and age of the pavement surface on which sealant was installed. However, it mostly depends on the maintenance and pavement preservation plan of the agency, which often is dictated by the budget. Appendix O and Appendix P present the service periods for the different rout-and-seal and clean-and-seal projects considered.

Figure 4.13 shows the average service period of rout-and-seal and clean-and seal projects. It may be stated that only 12 clean-and-seal projects were available to compare with 26 rout-and-seal projects; therefore, a strong conclusion on the service period of the clean-and-seal method (at least from this exercise) may not be justified. Within the available dataset, the average of service periods for both the methods was found to be similar, which is close to 6 years. The statistical analysis (ANOVA) conducted upon the results of service periods of rout-and-seal and clean-and-seal projects also did not show any significant difference (Table 5). Although this could be an oversimplification, it appeared that MnDOT usually considers a follow-up treatment approximately after six years of the crack treatment.

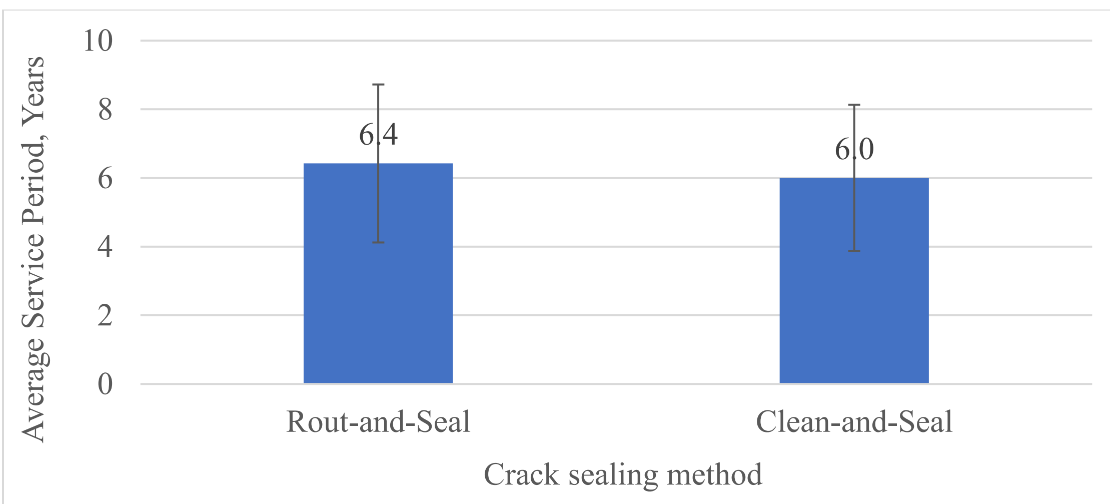


Figure 4.13: Average Service Period of Rout-and-seal and Clean-and-seal Projects

Table 5: ANOVA Results – Service Period of Rout-and-seal and Clean-and-seal Projects

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
R&S	26	167	6.42308	5.29385
C&S	12	72	6	4.54545

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.46964	1	1.46964	0.29015	0.59344	4.11317
Within Groups	182.346	36	5.06517			
Total	183.816	37				

*Note: P-value < 0.05 indicates a significant difference between the groups

Table 6 shows the descriptive statistics of service periods of rout-and-seal and clean-and-seal projects. The service periods of rout-and-seal projects vary between 3 and 11 years; whereas clean-and-seal projects vary between 5 and 11 years. The service periods, at 95% confidence level, for these projects were found to be 5.5 - 7.4 years for rout-and-seal, and 4.6 -7.4 years for clean-and-seal. Figure 4.14 and Figure 4.15 show the histogram of service periods of these methods.

Table 6: Descriptive Statistics – Service Periods of Rout-and-seal and Clean-and-seal

Descriptive	Rout-and-seal	Clean-and-seal
Mean	6.4	6.0
Standard Error	0.451	0.615
Median	6.0	5.0
Mode	6.0	5.0
Standard Deviation	2.301	2.132
Sample Variance	5.294	4.545
Kurtosis	-0.701	2.754
Skewness	-0.032	2.026
Range	8	6
Minimum	3	5
Maximum	11	11
Sum	167	72
Count	26	12
Confidence Level (95.0%)	0.929	1.355

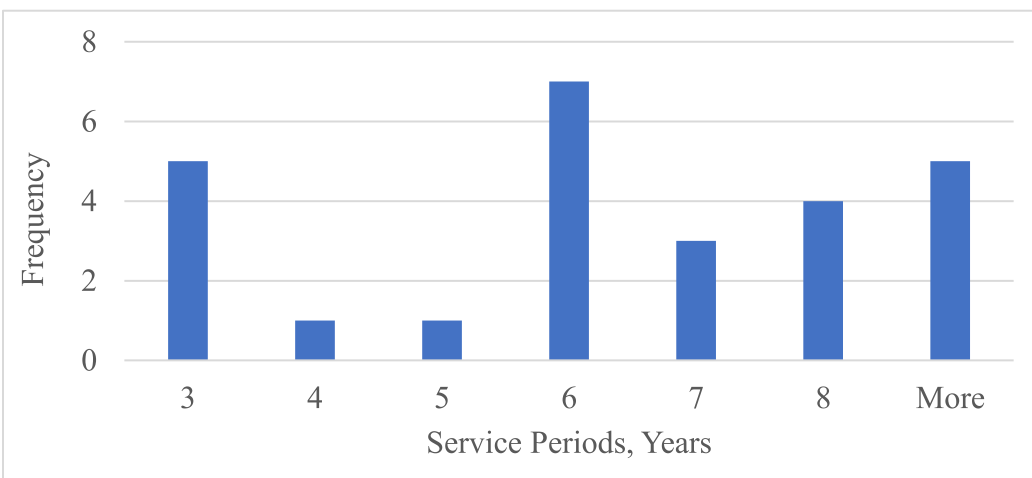


Figure 4.14: Histogram – Service Periods of Rout-and-Seal Projects

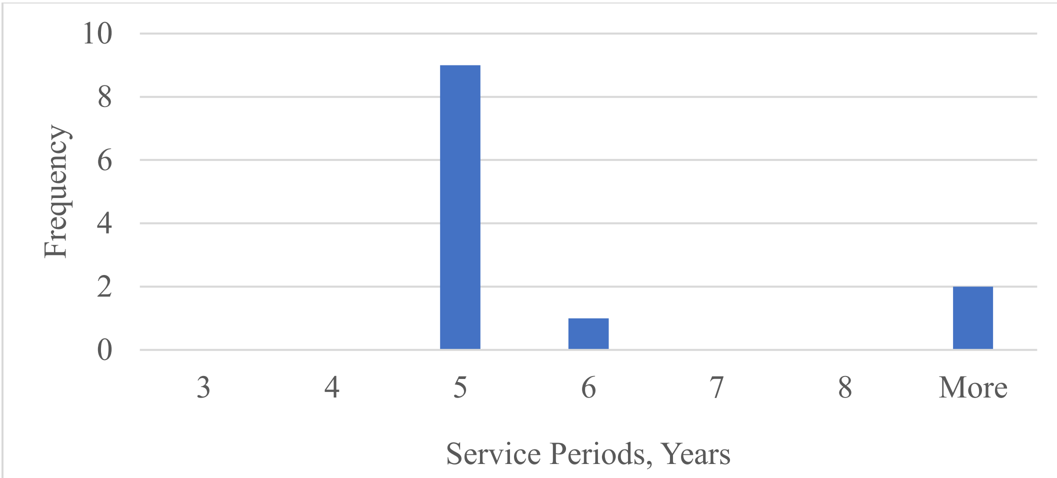


Figure 4.15: Histogram – Service Periods of Clean-and-Seal Projects

Influence of Traffic on the Service Period

Figure 4.16 shows the average service periods of rout-and-seal and clean-and-seal projects with respect to traffic categories, below and above 10,000 AADT. The average service period for the rout-and-seal and clean-and-seal are similar though, approximately one year higher for the roads with less than 10,000 AADT. The statistical analysis conducted on different combinations such as within and between rout-and-seal and clean-and-seal methods did not show any significant difference (P-value > 0.05) at a 95% level of confidence (Table 7). Additionally, no clear correlation was found between the AADT and service period (Figure 2.12 to Figure 2.17) for both of the sealing methods.

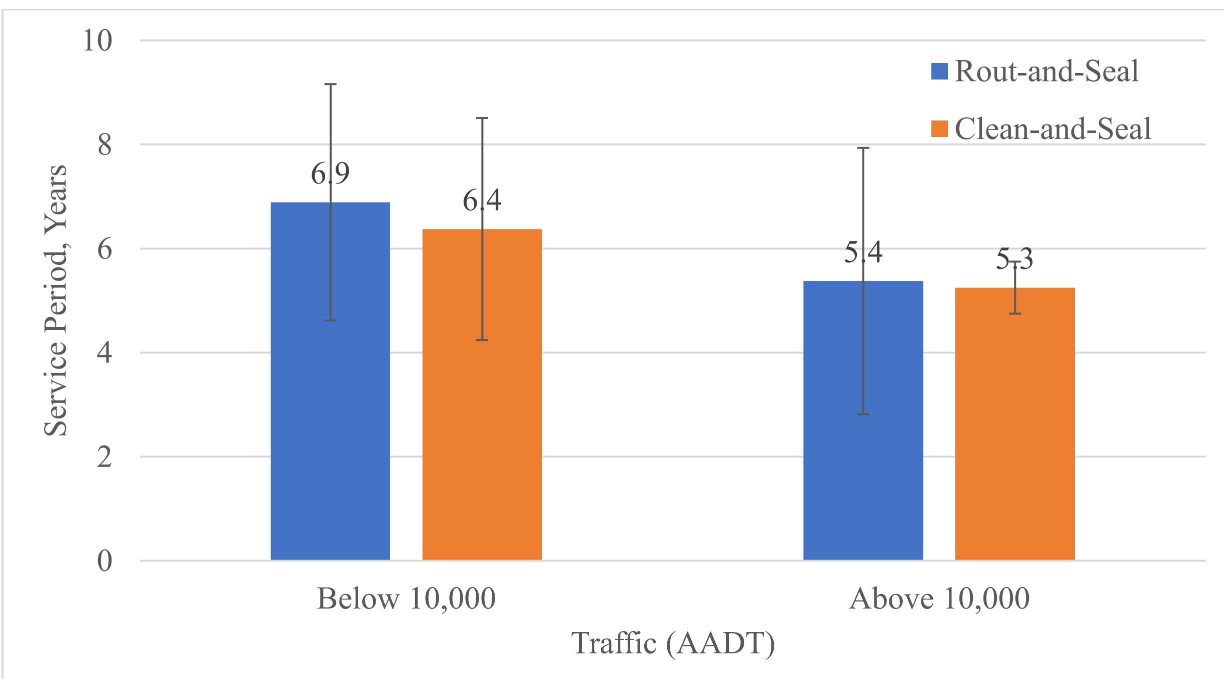


Figure 4.16: Service Period vs. Traffic (AADT) – Crack Sealing Methods

Table 7: ANOVA Results – Service Period of R&S and C&S with respect to Traffic

	SS	*df*	*MS*	*F*	*P-value*	*F crit*
Below 10,000 AADT (Rout-and-seal Vs. Clean-and-seal)						
Between Groups	1.46261	1	1.46261	0.26264	0.613	4.25968
Within Groups	133.653	24	5.56887			
Above 10,000 AADT (Rout-and-seal Vs. Clean-and-seal)						
Between Groups	0.04167	1	0.04167	0.01277	0.91226	4.9646
Within Groups	32.625	10	3.2625			
Rout-and-seal (Below 10,000 AADT Vs. Above 10,000 AADT)						
Between Groups	12.6934	1	12.6934	2.54604	0.12366	4.25968
Within Groups	119.653	24	4.98553			
Clean-and-seal (Below 10,000 AADT Vs. Above 10,000 AADT)						
Between Groups	3.375	1	3.375	0.72386	0.41479	4.9646
Within Groups	46.625	10	4.6625			

*Note: P-value < 0.05 indicates a significant difference between the groups

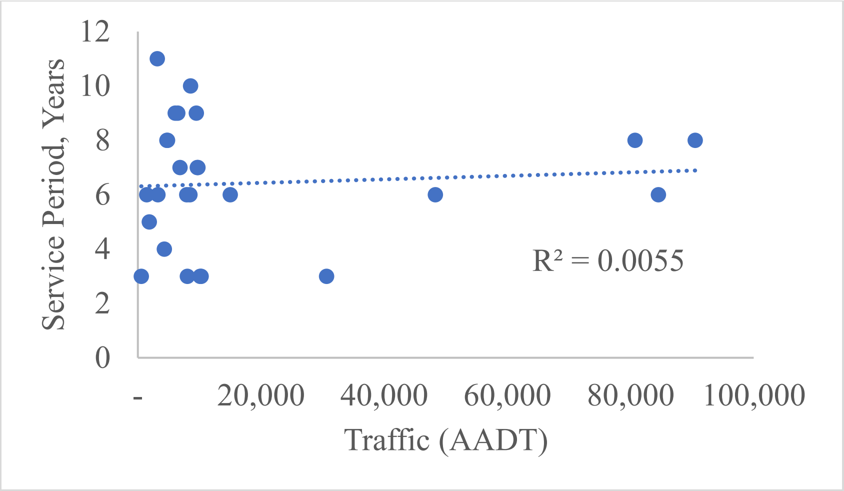


Figure 4.17: Service Period vs. Traffic (AADT) - All, Rout-and-seal Projects

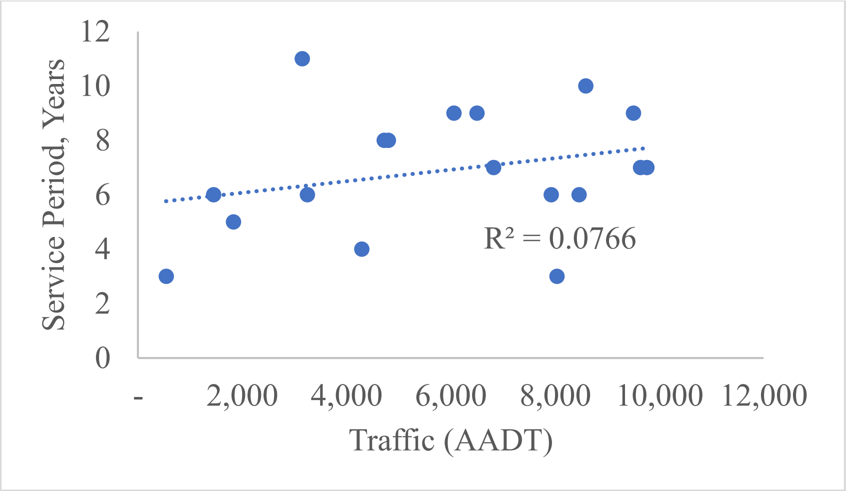


Figure 4.18: Service Period vs. Traffic (AADT) – Below 10,000, Rout-and-seal Projects

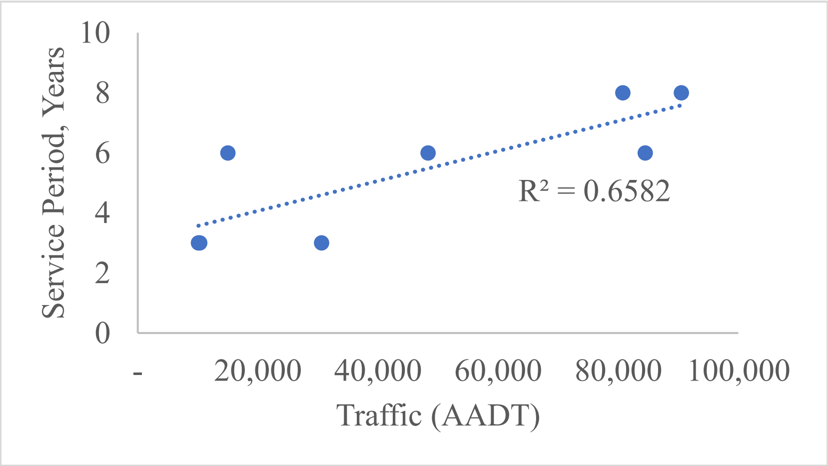


Figure 4.20: Service Period vs. Traffic (AADT) – Above 10,000, Rout-and-seal Projects

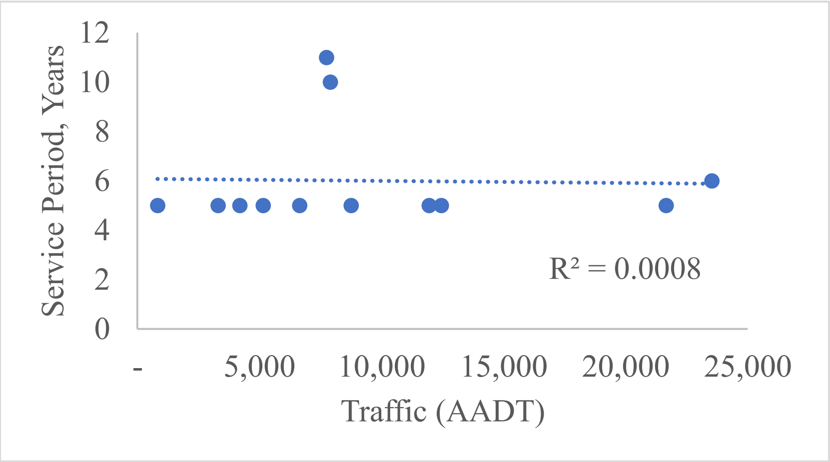


Figure 4.19: Service Period vs. Traffic (AADT) - All, Clean-and-seal Projects

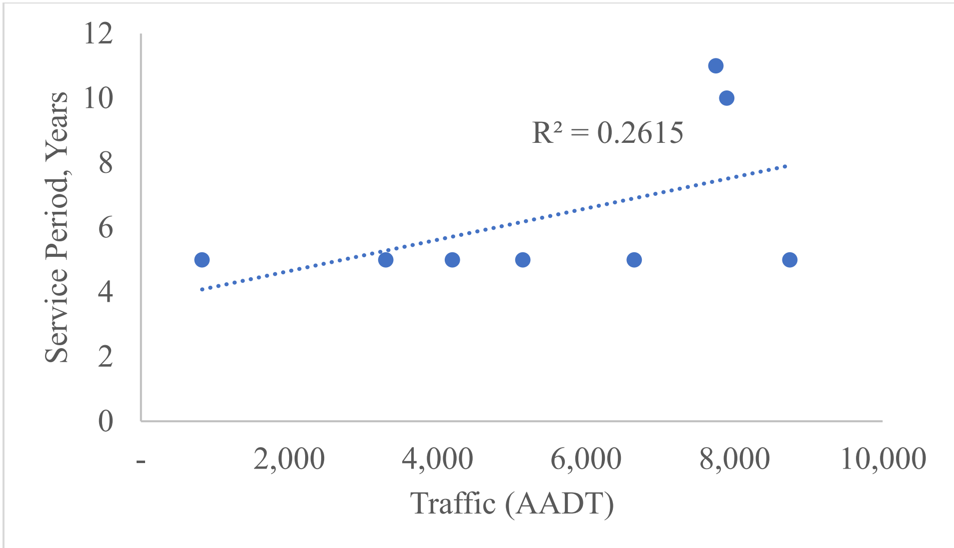


Figure 4.21: Service Period vs. Traffic (AADT) – Below 10,000, Clean-and-seal Projects

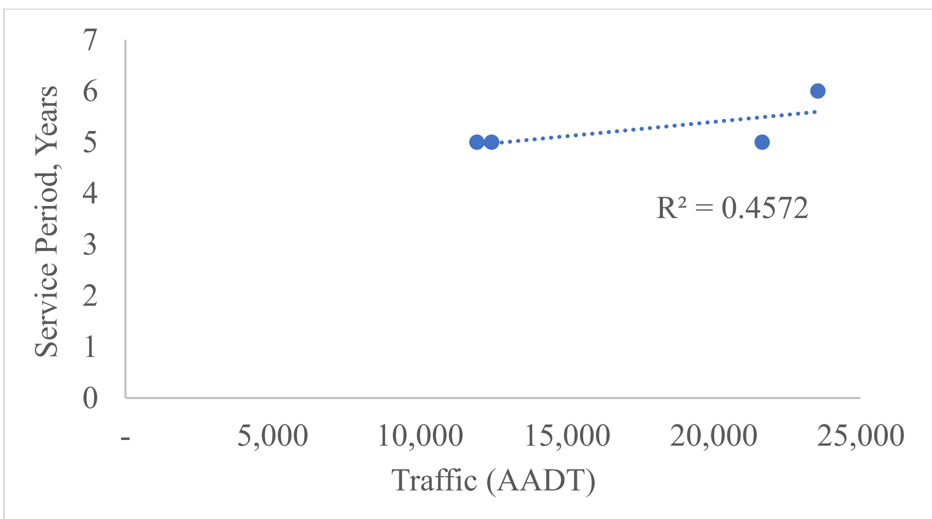


Figure 4.22: Service Period vs. Traffic (AADT) – Above 10,000, Clean-and-seal Projects

Influence of Pavement Surface Layer Thickness on the Service Period

Figure 4.23 and Figure 4.24 show the results of service Period vs. pavement surface layer thickness for rout-and-seal and clean-and-seal projects. No significant correlation between the pavement surface layer thickness and service period was found either.

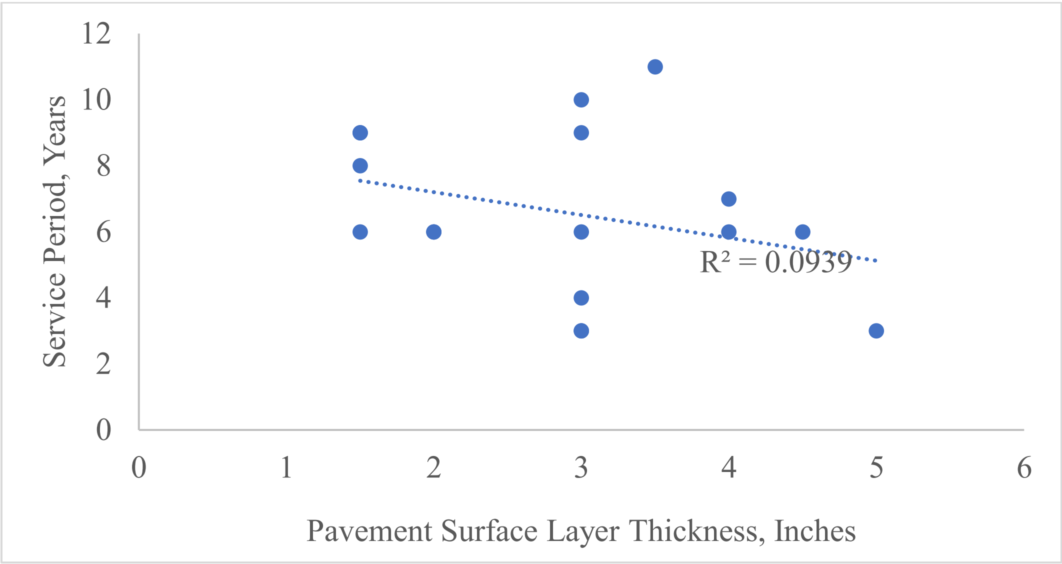


Figure 4.23: Service Period vs. Pavement Surface Layer Thickness, Rout-and-seal Projects

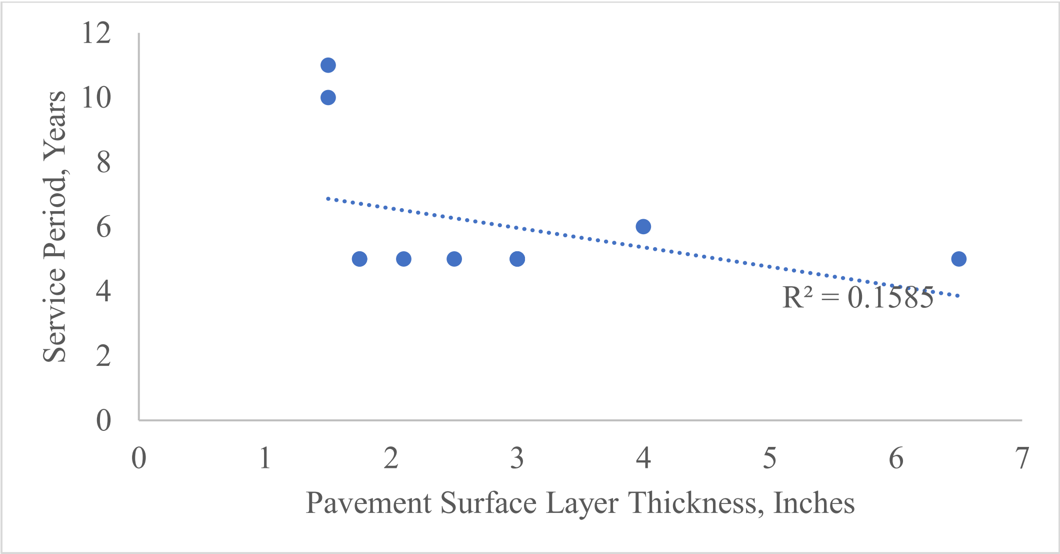


Figure 4.24: Service Period vs. Pavement Surface Layer Thickness, Clean-and-seal Projects

Influence of the Pavement Surface Layer Age on the Service Period of Crack Sealants

Figure 4.25 and Figure 4.26 show the results of service period vs. pavement surface layer age for rout-and-seal and clean-and-seal projects, respectively. Also in this case, the plots did not show any clear correlation for both the sealing methods within the available dataset; except for indicating a slightly declining service period for older pavement surfaces.

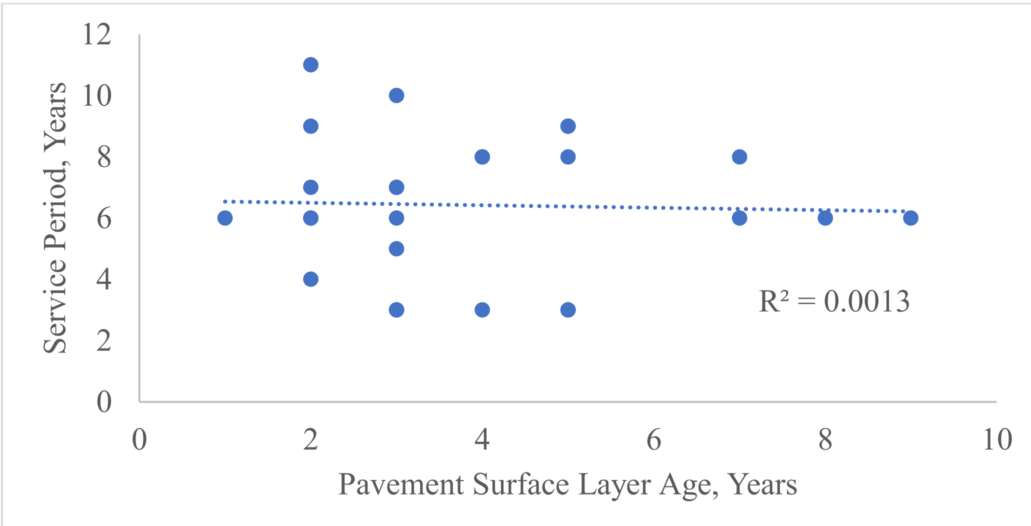


Figure 4.25: Service Period vs. Pavement Surface Layer Age, Rout-and-seal Projects

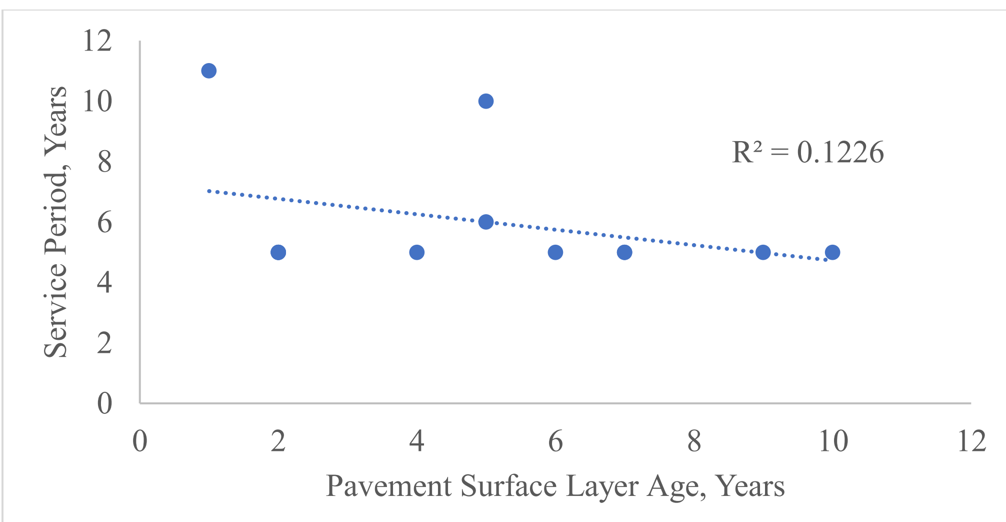


Figure 4.26: Service Period vs. Pavement Surface Layer Age, Clean-and-seal Projects

4.3 PHASE 3: NEWLY-INSTALLED CRACK SEAL SITES

The performance evaluations of 11 newly-installed crack sealing sites are presented in this section. All of these sites were sealed in the summer and fall of 2017. Figure 4.27 shows the locations of these sites. Yellow, green, and red pins represent the locations of the sites sealed with the rout-and-seal method only, the clean-and-seal method only, and both the methods. The research team visited these sites during the sealant installation. Many data, such as sealing procedures, materials, sites, and crack locations were documented at the project sites. A copy of the form used for data collection is attached in appendix R.

Following the sealant installation, additional visits were made to most of the 11 sites at various times: approximately 2 months (end of summer), 6 months (mid-winter), 8 months (end of winter), 12 months (second summer, and 18 months (during second winter) after the sealant application. On each visit, the length of the failed sealant and the failure type were documented. These data were used to determine the performance index (PI) for each sealed crack. The PI equation used in Al-Quadi et al. (2017) study was slightly modified for the current project to include the spalling failure, which has been noticed in multiple project sites unlike in other places. As shown in Equation 1, the performance index is a function of total crack length, cohesion loss, spalling, partial-depth adhesion loss, and full-depth adhesion loss.

$$PI = 100 - [(PFDA) + (PPDA * 0.5) + (PS) + PCL] \qquad (3)$$

Where:

PI = Performance Index

PFDA = Percent full depth adhesion loss by length

PPDA = percent partial depth adhesion loss by length

PS = Percent spalling by length

PCL = Percent cohesion loss by length

In this equation, percent partial-depth adhesion loss and percent cohesion loss are multiplied by a factor of 0.5 as it remains unclear if the seal remains water-tight or not by observation with the naked eye. Percent full-depth adhesion loss and percent spalling are multiplied by a factor of 1.

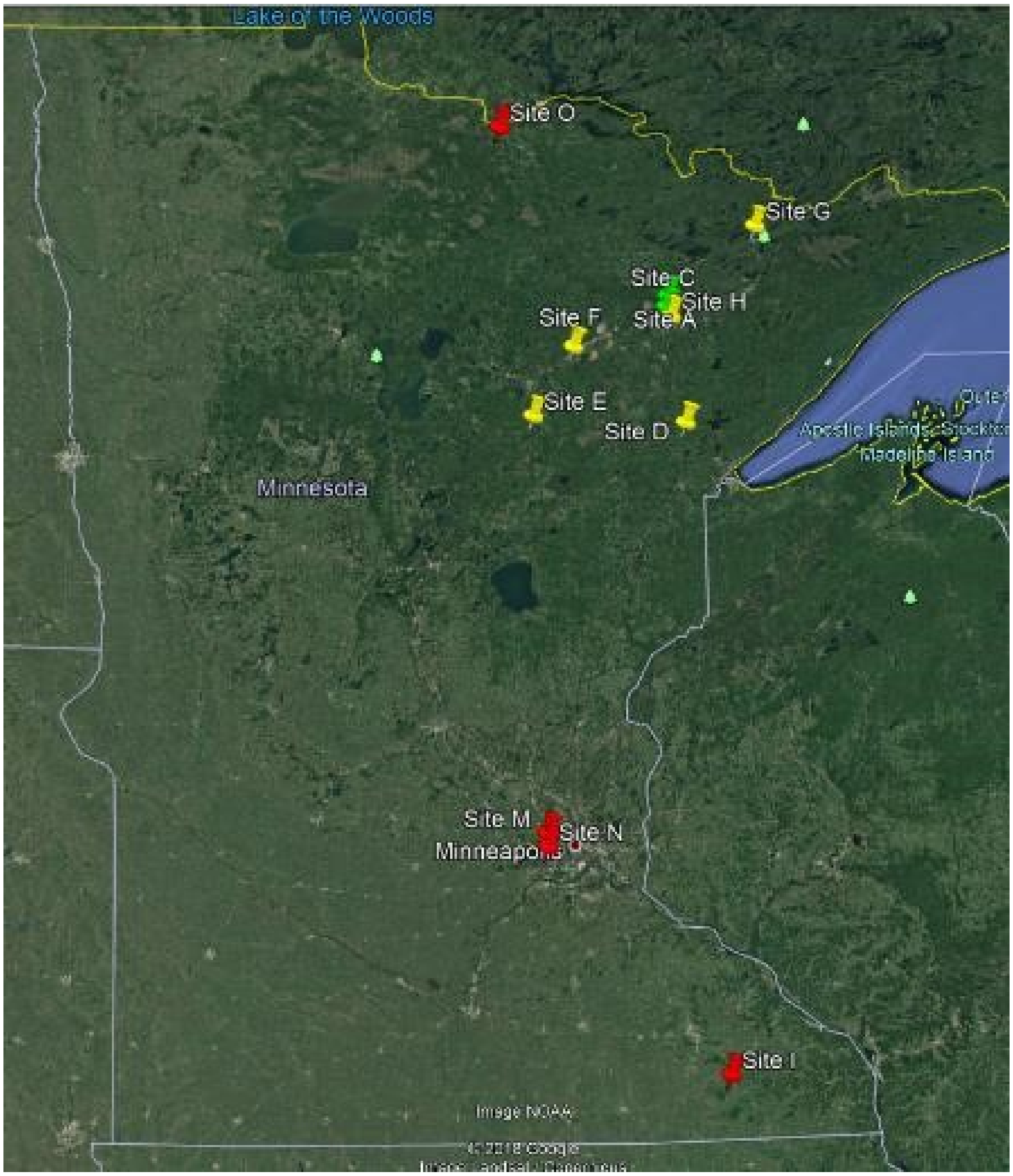


Figure 4.27: Locations of Newly-installed Crack Seal Field Sites

A sample performance documentation form is attached in Appendix Q. The performance criteria noted in these forms included plow abrasion, wheel-path flushing, pullout failure, full-depth adhesion loss, partial-depth adhesion loss, cohesion loss, spalling, and heaving. The majority of the distresses observed in the field sites included partial-depth adhesion loss, full-depth adhesion loss, and spalling. Examples of the abovementioned failure types are shown in Figure 4.28. Some cohesion failures were observed in a few clean-and-seal cracks. Early signs of cohesion failures were observed on a few rout-and-seal cracks; however, the cohesion loss only extended through the upper portion of routed reservoirs, still allowing the seals to remain watertight. These early signs of cohesion failure were not included in the performance index calculation. An example of the cohesion failure observed is shown in Figure 4.29.

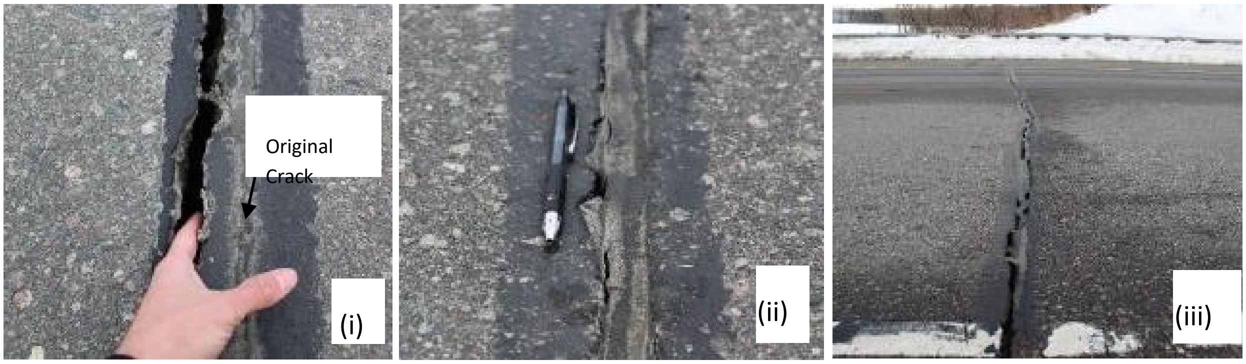


Figure 4.28: Examples of Seal Failures (i) Spalling, (ii) Partial Adhesion Loss, (iii) Full-depth Adhesion Loss.)

Figure 4.29: (i) Cohesion Failure of Clean-and-Seal Crack (ii) Early Signs of Cohesion Failure on Rout-and-Seal Crack

In addition to recording measurements, efforts were made to take photographs of each crack during each field visit. Placing these photographs side-by-side allows for a visual interpretation of seal degradation with respect to time. Photographs could not be collected from every crack in each site visit because of traffic, weather, and limited visibility of crack ID numbers in some sites due to snow on pavement and shoulders. The construction history of the pavement surface layer and traffic for these sites, if available, was obtained from MnDOT databases as described in Section 4.2.2 .

The performance index for every crack of all the project sites was calculated using Equation 3. The following subsections discuss the performance evaluations of Site E, and Site O. Site E has been selected for the representation of rout-and-seal sites while Site O has been chosen to represent sites containing both cracks sealing methods. The data for all other sites are included Appendix S. The data for each site is presented in tables, graphs, and pie charts. Rows that are highlighted red have been excluded from the overall analysis of each site, as these cracks are mainly longitudinal, treated with filling, and fail differently than the primary thermally induced transverse cracks.

4.3.1 Performance Analysis for Site E

Site E is located on TH 200 between miles 176 and 180 which has an AADT of 1,200. The site contains ten documented cracks. Nine of the cracks were sealed with the rout-and-seal method and one crack, along the lane joint, left untreated. The sealed cracks ran in the transverse direction and were of low severity.

All the cracks were sealed with MnDOT 3725 sealant. Three trucks were used in the sealing operation in that project site. One truck would drive 10-15 minutes ahead of the other two, filling the routed reservoirs half full of sealant. The second truck would fill the reservoir and apply toilet paper over the freshly sealed crack. The third truck performed filling on longitudinal cracks in a single pass.

The most recent construction data for this site includes an asphalt surfacing in 1999 followed by crack sealing in 2001. The next rehabilitation performed on this section of road was a 1.5-inch mill and 3.5-inch asphalt overlay in 2012 on which the crack sealants were installed in 2017. Information on each of the ten cracks is shown in Table 8.

Table 8: Documented Cracks in Site E

Site E							
ID#	Crack Location	Cack Type	AVG Width (mm)	Severity	AADT	Repair Type	Sealant Material
E-1	TH 200 RP 176.95	Thermal	3.25	low	1200	Rout-and-Seal	MNDOT 3725
E-2	TH 200 RP 176.95	Thermal	3.75	low	1200	Rout-and-Seal	MNDOT 3725
E-3	TH 200 RP 177.01	Thermal	7.5	low	1200	Rout-and-Seal	MNDOT 3725
E-4	TH 200 RP 177.05	Thermal	7	low	1200	Rout-and-Seal	MNDOT 3725
E-5	TH 200 RP 177.10	Lane Joint	6.5	low	1200	none	MNDOT 3725
E-6	TH 200 RP 179.95	Thermal	4.25	low	1200	Rout-and-Seal	MNDOT 3725
E-7	TH 200 RP 179.95	Thermal	6	low	1200	Rout-and-Seal	MNDOT 3725
E-8	TH 200 RP 180	Thermal	5.5	low	1200	Rout-and-Seal	MNDOT 3725
E-9	TH 200 RP 180	Thermal	5	low	1200	Rout-and-Seal	MNDOT 3725
E-10	TH 200 RP 180	Thermal	5	low	1200	Rout-and-Seal	MNDOT 3725

The data on the most recent site visit (second winter) is presented in Table 9 and Figure 4.30 below. In this site, noticeable amounts of adhesion and spalling failures had occurred in the first winter itself. The performance index vs. seal age is plotted in Figure 4.31. Figure 4.32 shows the photographs of the cracks during installation, during the first winter, and during the second winter since installation. This figure indicates that the PI dropped first time during the first winter and then remained the same until the next winter when it dropped again by 10 to 20%.

Table 9: Performance of Site E after Second Winter

Site E Performance (end of 2nd Winter)						
Crack ID	crack lengt	Length PDA	Length FDA	Length Spalling	Unfailed length	Performance Index
E-1	12	1.5	3	1.5	6	56.25
E-2	12	1.5	3	0	7.5	68.75
E-3	12	2	3	2	5	50.00
E-4	12	0	1	0	11	91.67
E-5	90				90	x
E-6	12	1	3	1	7	62.50
E-7	12	1	3	1	7	62.50
E-8	12	3	0	0.5	8.5	83.33
E-9	12	0.5	0	2	9.5	81.25
E-10	12	3	0.5	0.5	8	79.17
sum	108	13.5	16.5	8.5	69.5	70.60

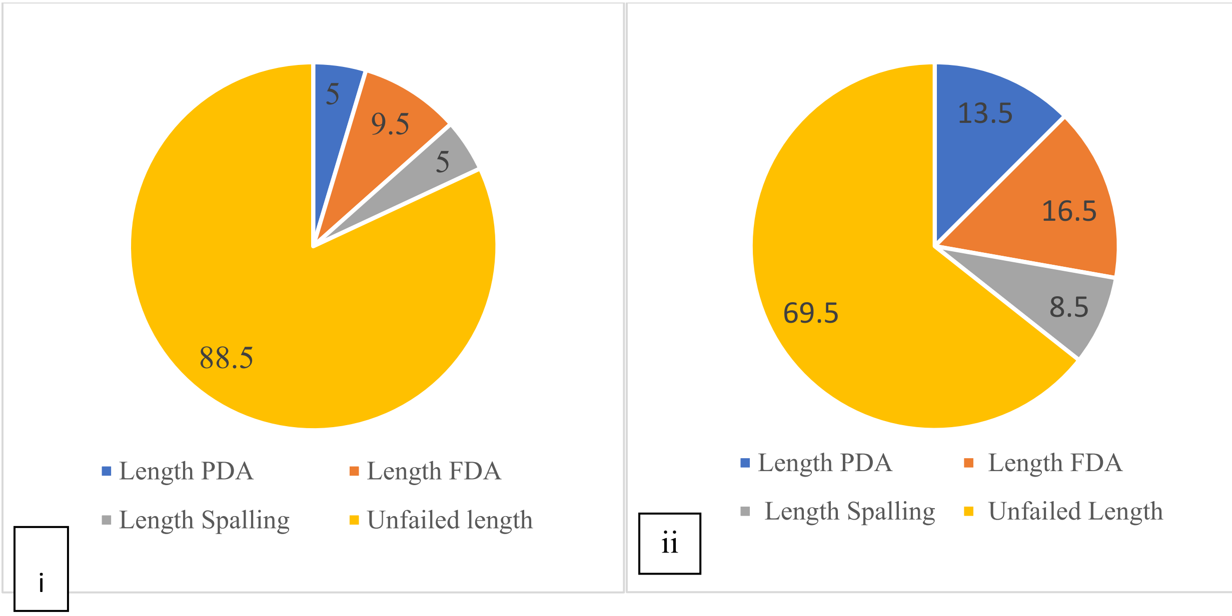


Figure 4.30: Seal Performance at Site E after (i) First Winter, and (ii) Second Winter

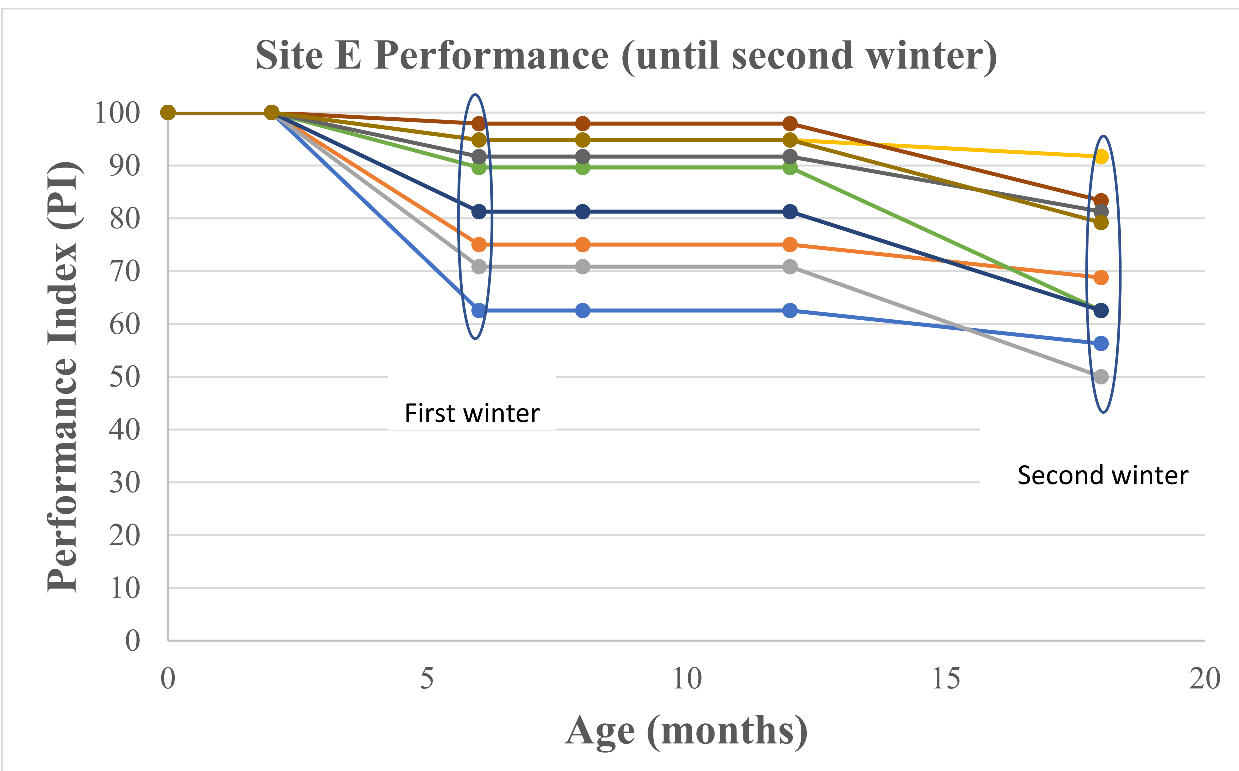
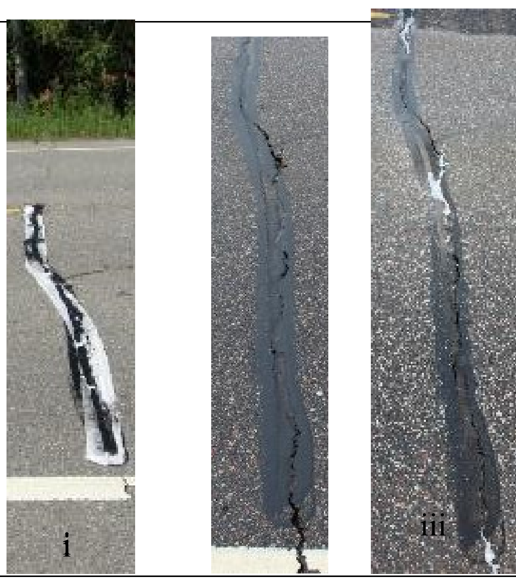


Figure 4.31: Site E Performance Index of Site E after the Second Winter

E-1	E-2
	
E-3	E-4
	
E-5	E-6

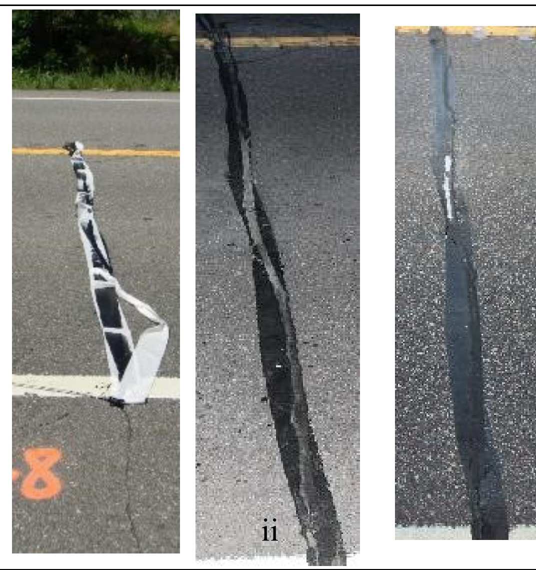
	
E-7	E-8
	
E-9	E-10

Figure 4.32: Photographic Performance Documentation of Site E. E-1-i Shows Crack E-1 upon being sealed. E-1-ii and E-1-iii show Crack E-1 at the end of its first winter and during the second winter after being sealed. This same sequence of photos follows for cracks E-2, E-3, E-4, E-5, E-6, E-7, E-8, E-9, and E-10. E-10-iv shows the seal performance at the end of the first winter compared to the mid-winter performance presented in E-10-iii.

4.3.2 Performance Analysis for Site O

Site O is located on CR 10 in Koochiching County, MN, which is a rural section of road. The AADT is around 100, and no construction history was found. The pavement surface appears to be quite old though, with crack spacing approximately ranging from 5 - 10 feet. This site consists of 20 documented cracks, all of which cracks run in the transverse direction. Ten of the twenty were sealed with clean-and-seal and the remaining ten were sealed with rout-and-seal. Information on each of the twenty cracks is shown in Table 10. The data on the most recent site visit (second winter) is presented in

Table 11. The performance evaluation of this site for the first and second winter, for both crack sealing methods, are presented in Figure 4.33 through Figure 4.35. This site experienced minimal failure in the first winter. However, the following more severe second winter had caused significant expansion of the crack width and failed many seals as a result. The performance data collected during the second winter visit of Site O indicates that the clean-and-seal deteriorated much faster than a rout-an-seal. The increased amounts of failures seen in the clean-and-seal cracks at this site included full and partial depth adhesion failures as well as cohesion failures. This was the only site where cohesion failure was observed, and the cohesion failure was only observed on the clean-and-seal cracks.

Table 10: Documented Cracks in Site O

Site O							
ID#	Crack Location	Cack Type	AVG Width (mm)	Severity	AADT	Repair Type	Sealant Material
O-1	CR 10	thermal		med	80	Clean-and-Seal	
O-2	CR 10	thermal		med	80	Clean-and-Seal	
O-3	CR 10	thermal		med	80	Clean-and-Seal	
O-4	CR 10	thermal		med	80	Clean-and-Seal	
O-5	CR 10	thermal		med	80	Clean-and-Seal	
O-6	CR 10	thermal		med	80	Clean-and-Seal	
O-7	CR 10	thermal		med	80	Clean-and-Seal	
O-8	CR 10	thermal		med	80	Clean-and-Seal	
O-9	CR 10	thermal		med	80	Clean-and-Seal	
O-10	CR 10	thermal		med	80	Clean-and-Seal	
O-11	CR 10	thermal		med	80	Rout-and-Seal	
O-12	CR 10	thermal		med	80	Rout-and-Seal	
O-13	CR 10	thermal		med	80	Rout-and-Seal	
O-14	CR 10	thermal		med	80	Rout-and-Seal	
O-15	CR 10	thermal		med	80	Rout-and-Seal	
O-16	CR 10	thermal		med	80	Rout-and-Seal	
O-17	CR 10	thermal		med	80	Rout-and-Seal	
O-18	CR 10	thermal		med	80	Rout-and-Seal	
O-19	CR 10	thermal		med	80	Rout-and-Seal	
O-20	CR 10	thermal		med	80	Rout-and-Seal	

Table 11: Performance of Site O after Second Winter

Site O Performance (end of 2nd Winter) (clean-and-seal)							
Crack ID	crack length	Length PDA	Length FDA	Length Spalling	Length Cohesion	Unfailed length	Performance Index
O-1	12	0	0	0	0	12	100.0
O-2	12	6	0	0	0	6	75.0
O-3	12	8	0	0	0	4	66.7
O-4	12	2	5.5	0.5	1	3	41.7
O-5	12	3	0	0	1	8	100.0
O-6	12	1	0	0	0	11	95.8
O-7	12	2	0	0	0	10	91.7
O-8	12	1	0	0	0	11	95.8
O-9	12	1	0	0	0	11	91.7
O-10	12	2.5	0	0	0.5	9	79.2
sum	120	26.5	5.5	0.5	2.5	85	83.8
Site O Performance (end of 2nd Winter) (rout-and-seal)							
Crack ID	crack length	Length PDA	Length FDA	Length Spalling	Length Cohesion	Unfailed length	Peformance Index
O-11	12	0	0	0	0	12	100.0
O-12	12	0	0	0	0	12	100.0
O-13	12	1	0	0	0	11	95.8
O-14	12	0	0	0	0	12	100.0
O-15	12	0	0	0	0	12	100.0
O-16	12	1	0	0	0	11	95.8
O-17	12	1	0	0	0	11	95.8
O-18	12	1.5	0	0	0	10.5	93.8
O-19	12	0	0	0	0	12	100.0
O-20	12	1	0	0	0	11	99.5
sum	120	5.5	0	0	0	114.5	98.1

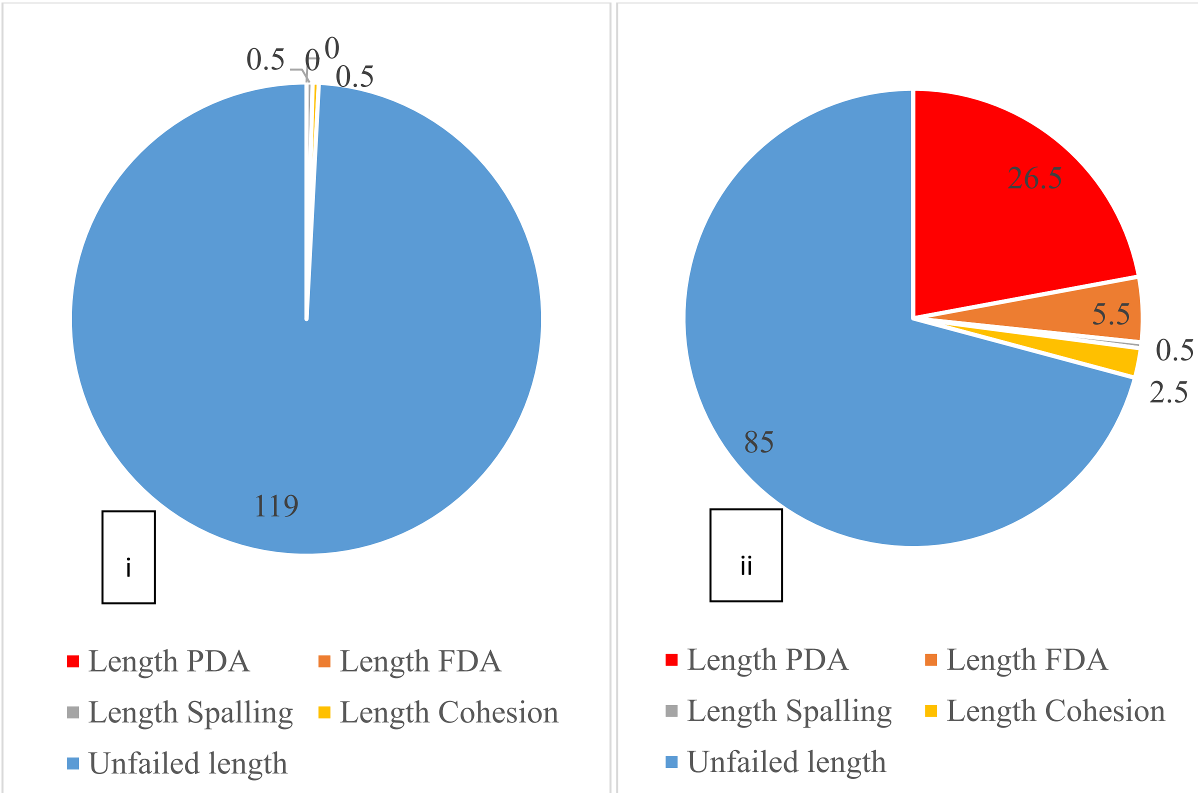


Figure 4.33: Site O Clean-and-Seal Performance, after First Winter (i) and Second Winter (ii)

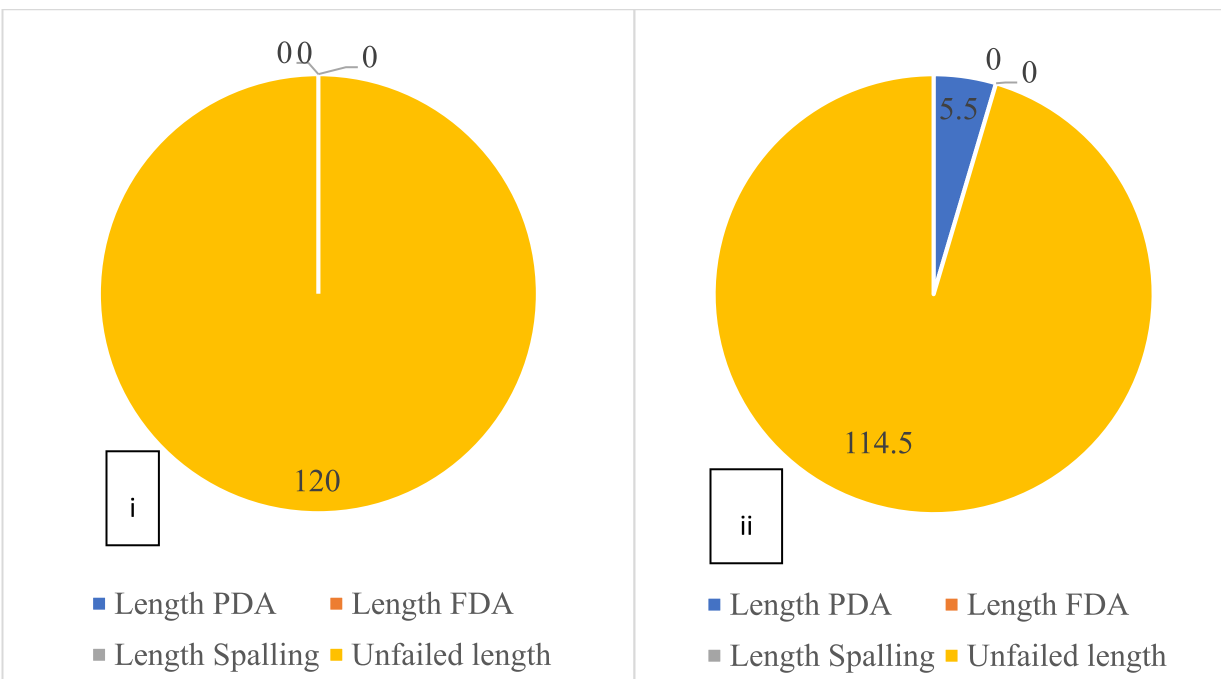


Figure 4.34: Site O Rout-and-Seal Performance After First Winter (i) and Second Winter (ii)

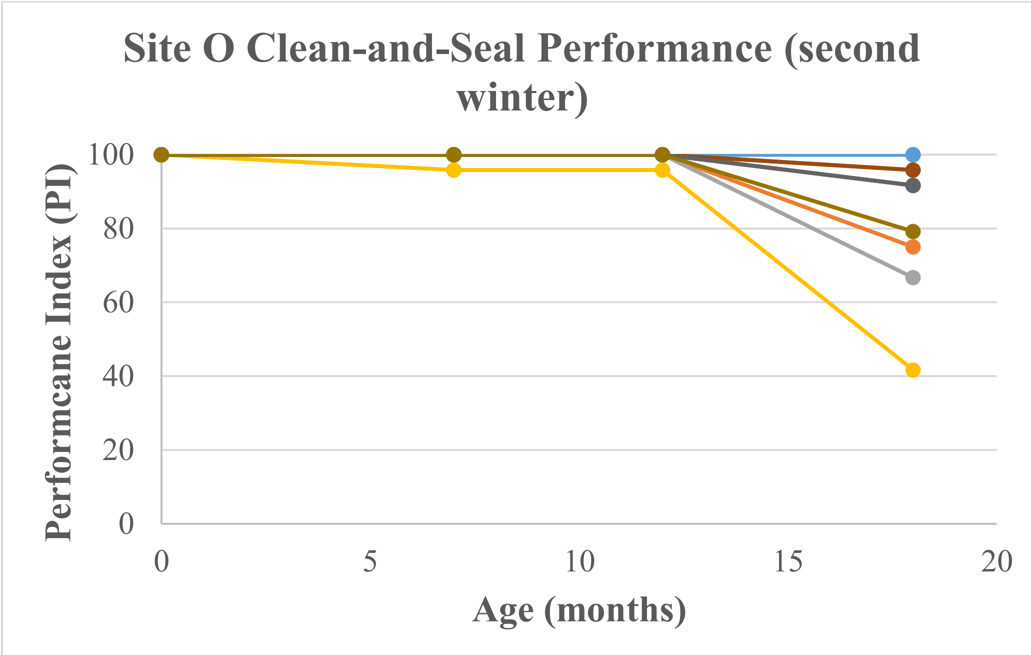


Figure 4.35: Site O Clean-and-Seal Performance Index of Site E after the Second Winter

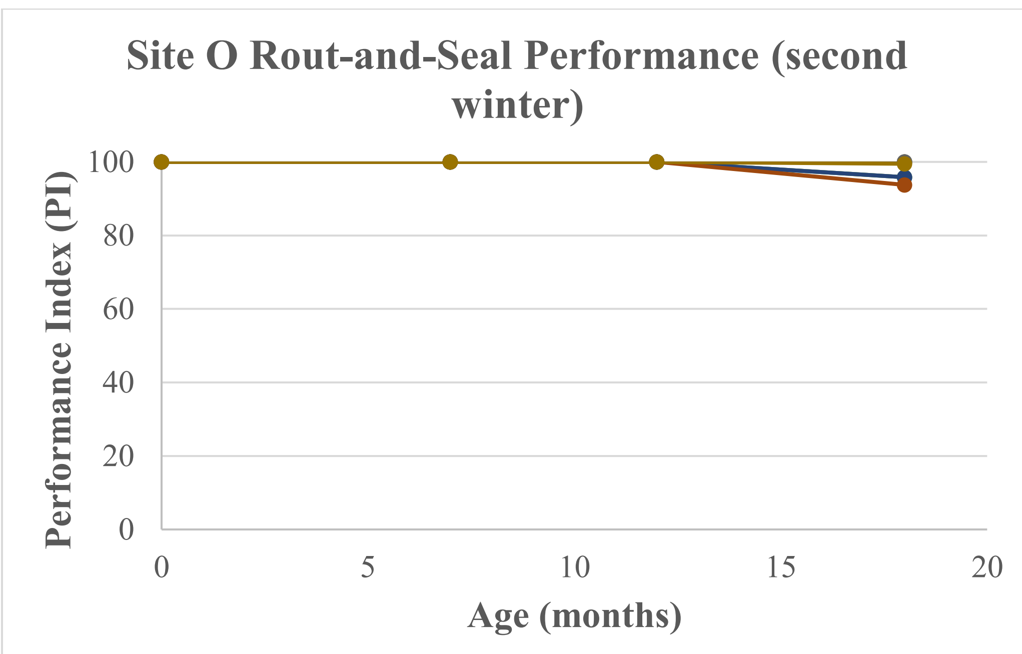


Figure 4.36: Site O Rout-and-Seal Performance Index of Site E after the Second Winter

4.3.3 Performance Summary of Newly-installed Crack Sealants

Similar to the Sites E and O, performance indices were calculated for all other sites. Table 12 provides a summary of the performance indices of all these sites along with available pavement and traffic information. After the first-year service (one summer and one winter), the average performance indices for rout-and-seal and clean-and-seal sites were found to be 85 and 90. As anticipated, the results from the second winter evaluations showed that the performance of the crack sealing is continuing to deteriorate with respect to time and expedited by the harsh winter. The rates of deterioration, however, were greater than that was anticipated, which is discussed further in section 5.1 of this report. As the winter of 2018 - 2019 in Minnesota was very severe (up to -70^{o}F wind chill), many of the cracks considered in this study expanded beyond their average winter expansion, which had failed many seals prematurely. The average performance indices for the second winter for rout-and-seal and clean-and-seal are 68.5 and 80.5, respectively. However, it should not be concluded that the clean-and-seal performed better than the rout-and-seal as the number of cracks sealed with rout-and-seal was much higher than its counterpart.

One of the common failures observed (primarily on rout-and-seal) was spalling. Although it was not formally addressed as a seal failure for calculating performance in other studies, spalling is contributing to a large portion of failure in the cracks documented for the current study. This failure likely occurs due to weakening of the asphalts along the sides of the routed reservoir, probably because of the mechanical agitations exerted on the asphalt by the router. The weak asphalt breaks due to the cyclic wheel load from the traffic and creates spalling. Cracks with rout-and-seal were also found to be experiencing a large amount of adhesion failures. This failure was seen more commonly with increased crack spacing. The overall performance on rural roads with closely spaced cracks was nearly identical for both clean-and-seal and rout-and-seal, except Site O. Cohesion failure has not been observed in any of the seals during the first 18 months of service.

Table 12: Summary of Performance Evaluations of Newly-installed Crack Sealing Project Sites

S. No.	Site	Route	Pavement Surface Layer			Crack Sealing		Traffic (AADT)	Avg. PI after 1st Winter	Avg. PI during 2nd Winter
			Year Paved	Description	Thickness (Inch)	Year Treated	Sealant type			
Clean-and-seal (C&S)										
1	A	US-53	2008	Bit. Overlay (2360)	1.5	2017	*C&S* (3723)	10,300	-	-
2	C	US-53	2008	Bit. Overlay (2360)	1.5	2017	*C&S* (3723)	16,100	100.0	-
3	I	CR 5	-	-	-	2017	*C&S* (3725) and R&S (3725)	-	99.5	99.0
4	M	-	-	-	-	2017	*C&S* and R&S*	-	78.5	8.0
5	N	-	-	-	-	2017	*C&S* and R&S*	-	75.0	58.0
6	O	CR 10	-	-	-	2017	*C&S* and R&S*	-	95.5	84.0
								Average	90.0	80.5
Rout-and-seal (R&S)										
1	D	US-53	2009	Concrete Overlay	8	2017	*R&S* (3725)	7,800	88.0	63.5
2	E	Mn-200	2012	Bit. Overlay (2360)	3.5	2017	*R&S* (3725)	1,200	84.0	71.0
3	F	US-169	2010	Bit. Surf. (2360)	Var.	2017	*R&S* (3725)	6,100	74.0	59.0
4	G	Mn-1	2014	Bit. Overlay (2360)	3	2017	*R&S* (3725)	2,300	67.0	40.0

5	H	TH 53	-	-	-	2017	*R&S* (3725)	-	95.0	63.5
6	I	CR5	-	-	-	2017	C&S (3725) and *R&S* (3725)	-	97.0	96.0
7	M	-	-	-	-	2017	*C&S* and R&S*	-	95.8	8.0
8	N	-	-	-	-	2017	*C&S* and R&S*	-	63.0	51.0
9	O	CR 10	-	-	-	2017	*C&S* and R&S*	-	100.0	98.0
								Average	85.0	68.5

4.4 PHASE 4: OLD CRACK SEAL SITES

This project also considered some old sealed cracks. Table 13 shows the list of crack seal sites considered in Phase 4; one representative crack was considered in the site. Sealants were installed in these sites between 2012 and 2017. These sites were located at the City of Duluth, Hutchinson, and Andover and had relatively lower AADT compared to some of the newly sealed project sites discussed in the previous section. All these sites were sealed with only the rout-and-seal method; suitable sites for clean-and-seal method could be found. An effort was made to collect various details such as sealing material, sealing procedure, costs, pavement, and traffic data. The sites in and around the City of Duluth were monitored for three seasons: spring 2018, fall 2018 and spring 2019; whereas sites in the two other cities were visited only once. The year of crack sealing for these sites were 2014, 2015, and 2016.

The methodology used for the performance evaluation of these sites was similar to what was followed for the newly-installed crack seal project sites in Phase 3, except documenting a few additional failures such as stone intrusion, pull-out failure, partial cohesion loss, and full cohesion loss. Examples of these failure types are shown below in Figure 4.37. Note that these specific failures were much visible during the fall season than spring season. The equation used for the performance index for the old crack sealing project sites is given below:

$$PI = 100 - [(PFDA) + (PPDA * 0.5) + (PS) + (PFCL * 0.5) + (PPCL * 0.25) + (PPF) + (PSI * 0.25)] \quad (4)$$

Where:

PFCL = Percent full cohesion loss by length

PPCL = Percent partial cohesion loss by length

PPF = Percent pull-out failure by length

PSI = Percent stone intrusion by length

Other variables were previously defined.

In this equation, percent full cohesion loss is multiplied by a factor of 0.5 since a portion of sealant remains watertight. The percent partial cohesion is multiplied by a factor of 0.25 since these cohesive cracks appear mostly on a surface level. The percent pull-out failure and the percent stone intrusion failure are multiplied by a reasonable factor of 1 and 0.25, respectively. All failure types were noted as a measurement of feet length.

Table 13: List of Old Crack Seal Project Sites Inspected during Field Visits

S. No.	Site ID	City/County	Project Location	Year of Crack Sealing
1	F	City of Duluth	Northridge Drive	2014
2	H	City of Duluth	Hickory Street	2014
3	J	City of Duluth	E Palm Street	2014
4	I	City of Duluth	S Blackman Street	2014
5	A	City of Duluth	3rd Street-21st AE to 1st AE	2014
6	B	City of Duluth	2nd Street -24th AE to Mesaba Avenue	2014
7	D	City of Duluth	Sundby Road-Maple Grove to Haines Road	2015
8	E	City of Duluth	Swan Lk Road-Arrowhead to Basswood	2015
9	C	City of Duluth	1st Street-21AE-8th AE	2015
10	L	City of Duluth	1st Street-24 to 26AE	2016
11	K	City of Duluth	2nd Street-24-26AE	2016
12	M	City of Duluth	3rd Street-24-26AE	2016
13	Q	City of Duluth	43AE Glenwood to Superior Street	2016
14	P	City of Duluth	45AE Glenwood to Superior Street	2016
15	O	City of Duluth	47AE Glenwood to Superior Street	2016
16	N	City of Duluth	52AE Oakley to Superior Street	2016
17	G1	City of Duluth	Arrowhead Road-Kenwood AV to Rice Lake Road (EB)	2016
18	G2	City of Duluth	Arrowhead Rd.-Kenwood AV to Rice Lake Road (WB)	2016

19	V1	City of Hutchinson	Segment 1: Hwy 22 to 1145 Michigan Street	2012
20	V2	City of Hutchinson	Segment 2: 1145 Michigan Street to 5th Avenue SE	2012
21	X	City of Hutchinson	1335 Jefferson Street SE	2017
22	Y	City of Andover	South coon creek Drive NW	2014
23	Z	City of Andover	Vale Street NW	2017
24	W	City of Andover	Wintergreen Street NW	2017

Note1: All these crack sealing treatments are rout-and-seal

(i) Stone Intrusion

(ii) Pull-out Failure

(iii) Partial Cohesion Loss

(iv) Full Cohesion Loss

Figure 4.37: Additional Seal Failure Types Observed in Old Crack Sealing Projects

4.4.1 Performance Analysis for Old Sites

Figure 4.38 shows photographs of conditions of a crack sealed in 2014 (Site J in Duluth) during the three different seasons mentioned above. Such photographs were also taken for all other cracks during each visit. PI was calculated using the documented information on the type and quantity of failure. Figure 4.39 shows the relation between PI and seal age for the sites sealed in 2014. It can be seen that the PI slightly decreased with time in all the six sites.

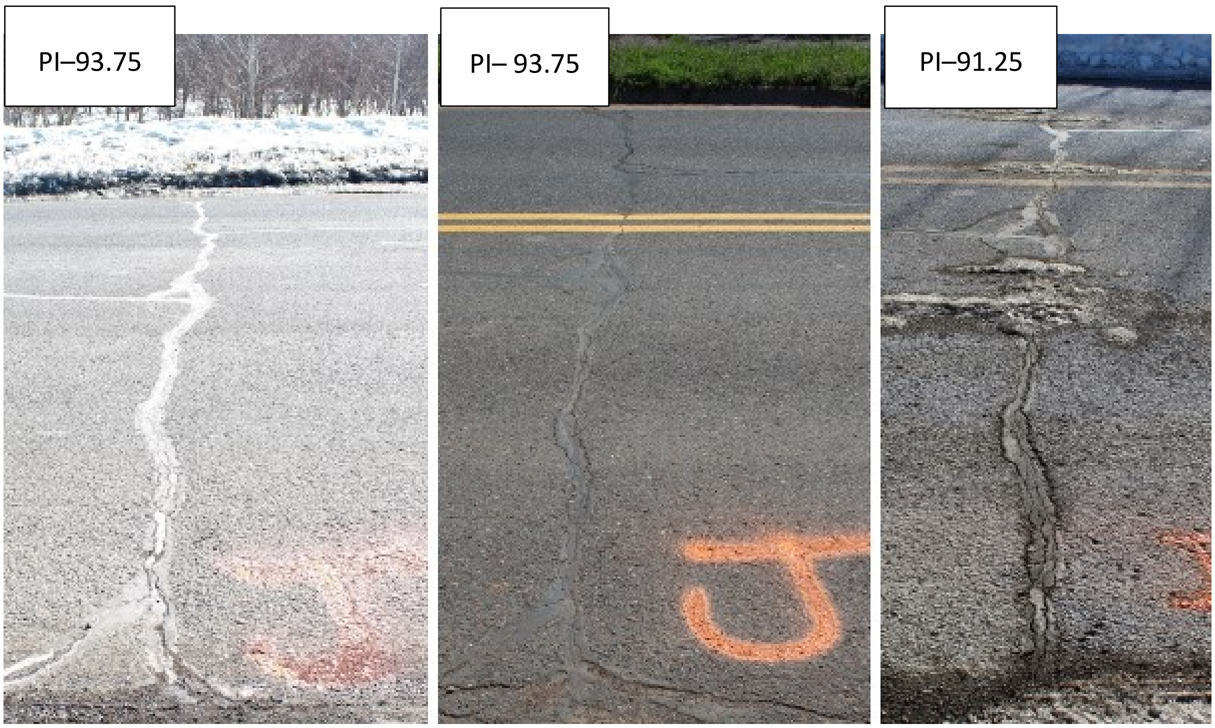


Figure 4.38: Site J- E Palm St., Duluth; Crack Sealing Year - 2014

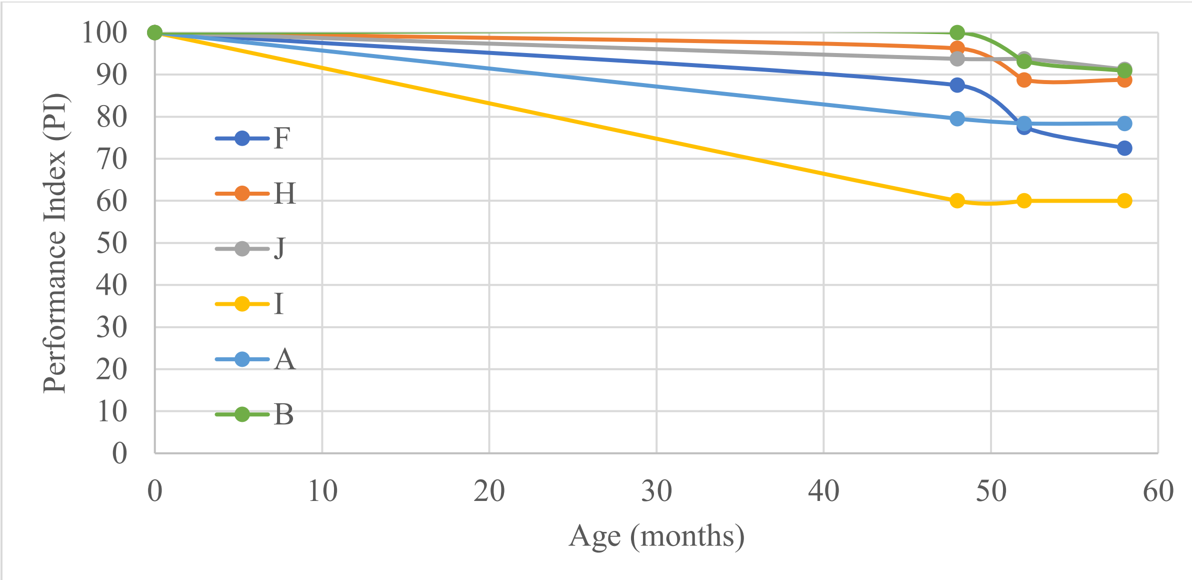


Figure 4.39: Performance Evaluations of 2014-year Crack sealing Projects

Figure 4.40 presents photographs of a crack sealed in the year 2015; a total of three sites were considered for the year 2015. Figure 4.41 shows that the PI of the two sites (Sites C and D) decreased by approximately 20%, and the PI in the other site significantly dropped to 10%.

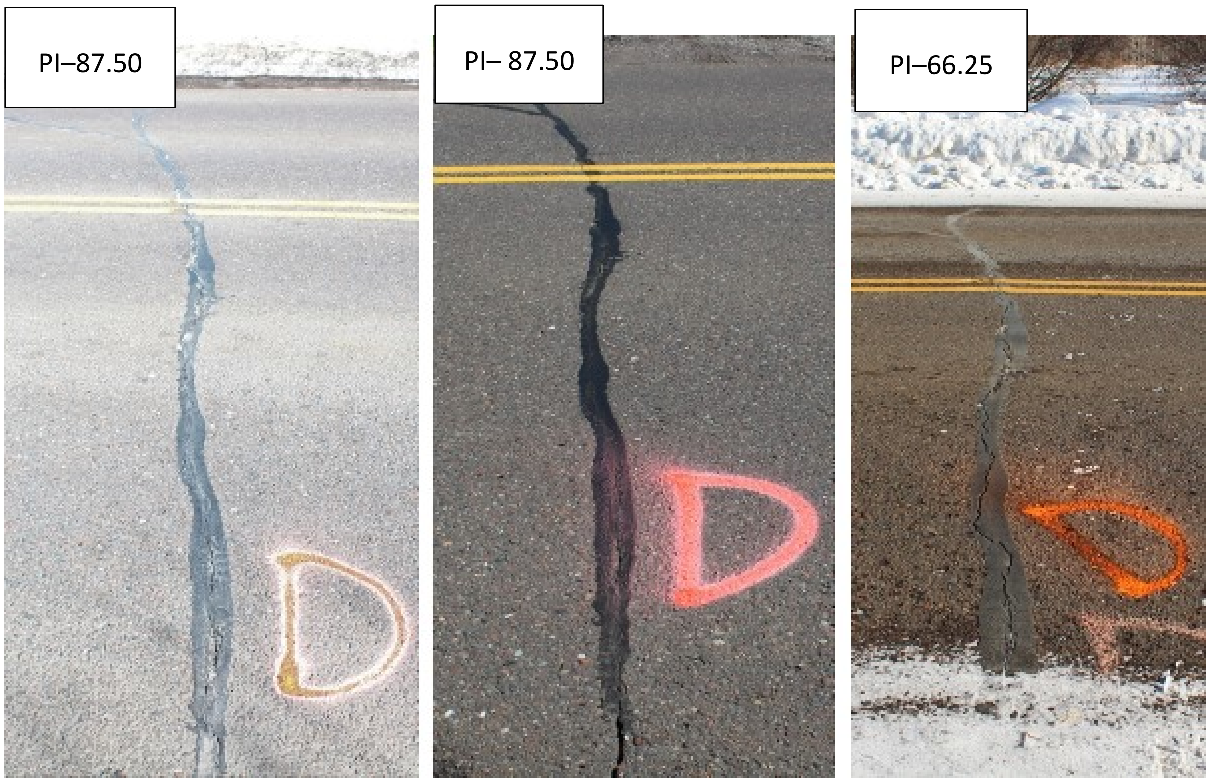


Figure 4.40: Site D- Sundby Rd., Duluth; Crack Sealing Year - 2015

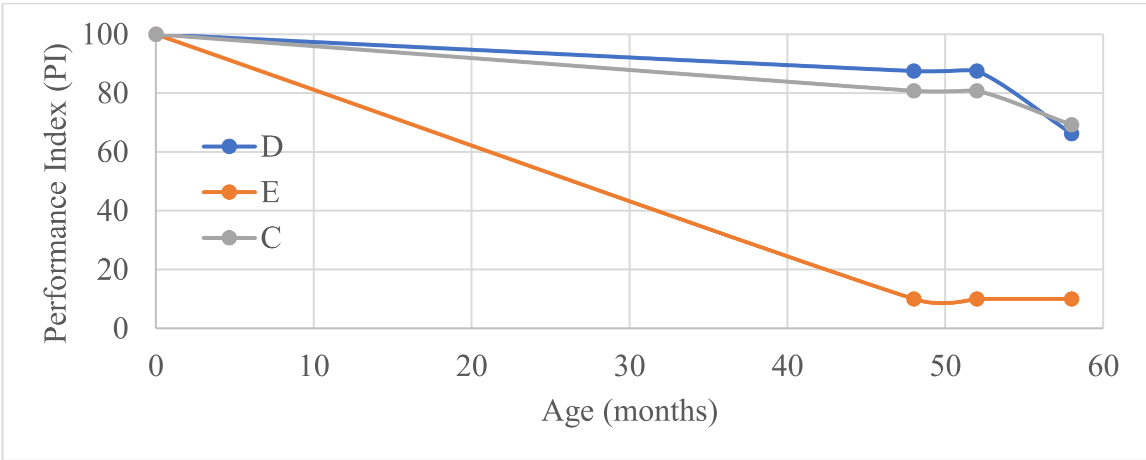


Figure 4.41: Performance Evaluations of 2015-year Crack sealing Projects

Figure 4.42 shows photographs of a crack sealed in the year 2016; a total of nine projects were considered for this year. Figure 4.43 shows that two of the nine sites experienced a decrease of approximately 60% of PI until the spring of 2019, while the other seven experienced variable but a lower drop in the PI. The PI of the Sites P and Q significantly dropped in the winter of 2018 – 2019.

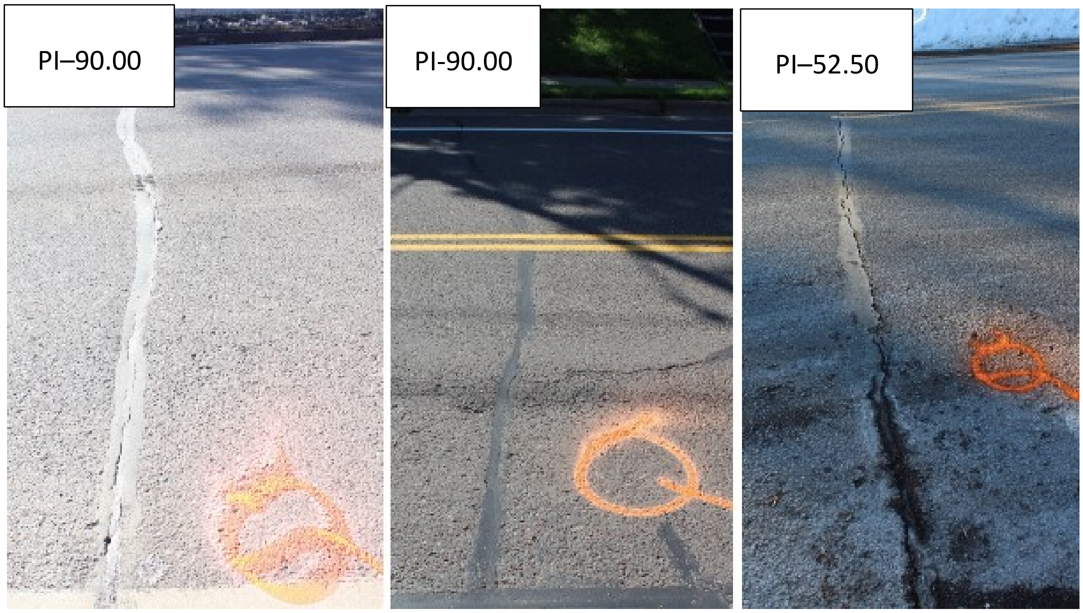


Figure 4.42: Site Q- 43AE Glenwood to Superior St., Duluth; Crack Sealing Year – 2016

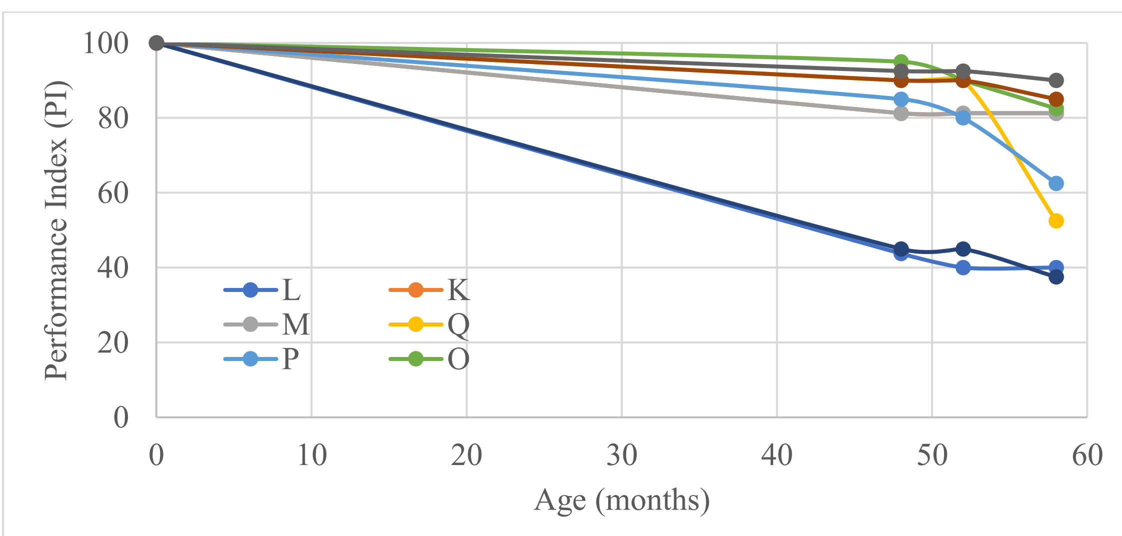


Figure 4.43: Performance Evaluations of 2016-year Crack sealing Projects

4.4.2 Performance Summary of Old Crack Seal Sites

Based on the sealant installation year and the last field visit year (Spring 2019), the ages of seals in the old crack seal sites are approximately 1 (sealed in 2017), 2, 3, 4, or 6 (sealed in 2012) years. Figure 4.44 shows the average PI for these projects with respect to the year of sealant installation. Note that due to the insufficient number of data points for the year 2012, the standard deviation was not determined. The PI vs age of seals appeared to be following a good and declining trend, except for the seals those were installed in 2014. The exact reason for this anomaly for the 2014 seals is unknown. However, the traffic volume of the roads (mainly residential streets) on which they belong was very low compared to the other roads.

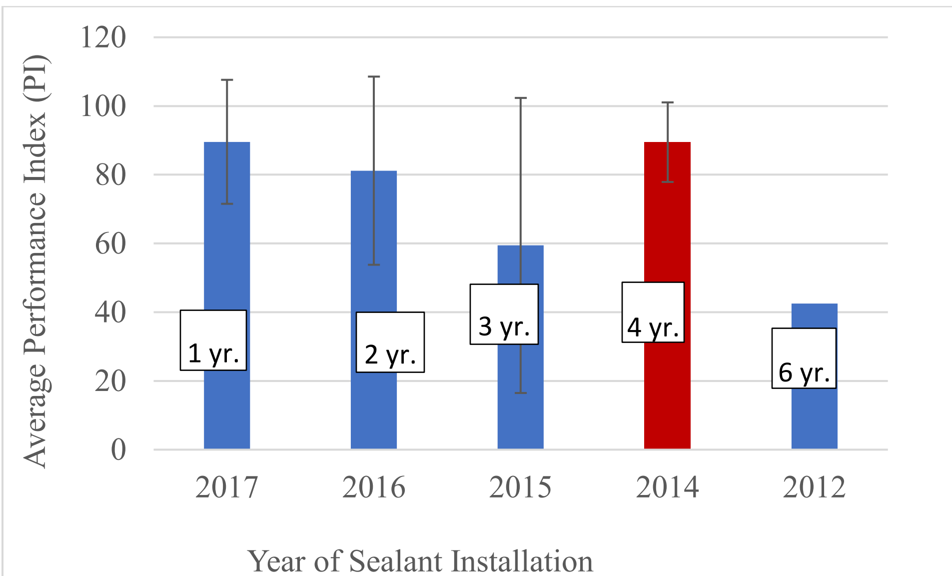


Figure 4.44: Yearly Average Performance Index (PI): Rout-and-seal Projects

4.4.2.1 Influence of Pavement Shoulder Type on the Crack Sealant

In order to understand the influence of the shoulder type on the performance of the sealant, a crack sealing site was visited in the city of Hutchinson where a road was sealed with rout-and-seal. The road had two segments, mainly differing on the shoulder type: (i) Segment 1- gravel shoulder (rural), and (ii) Segment 2- paved shoulder (urban) (Figure 4.45 and Figure 4.46). Even though both the segments received crack sealing treatment in the same year 2012, the rout-and-seal on rural segment showed complete failure; whereas, the urban segment was still in good condition when visited in 2018. Figure 4.47 shows the difference in performance index between these two segments. The City (John Olson, Personal Communication) believed that the performance difference could be primarily due to the improper drainage in Segment 1, where moisture could easily infiltrate through the gravel shoulder. Also, the 10-inch thick single full-depth asphalt pavement in Segment 2, as opposed to the 9-inch thick three-layer asphalt pavement structure (1.5-inch wear +1.5-inch binder + 6.0-inch base), could play a role too.

Figure 4.45: Segment 1-Hwy 22 to 1145 Michigan Street, Hutchinson

Figure 4.46: Segment 2-1145 Michigan Street to 5th Ave SE, Hutchinson

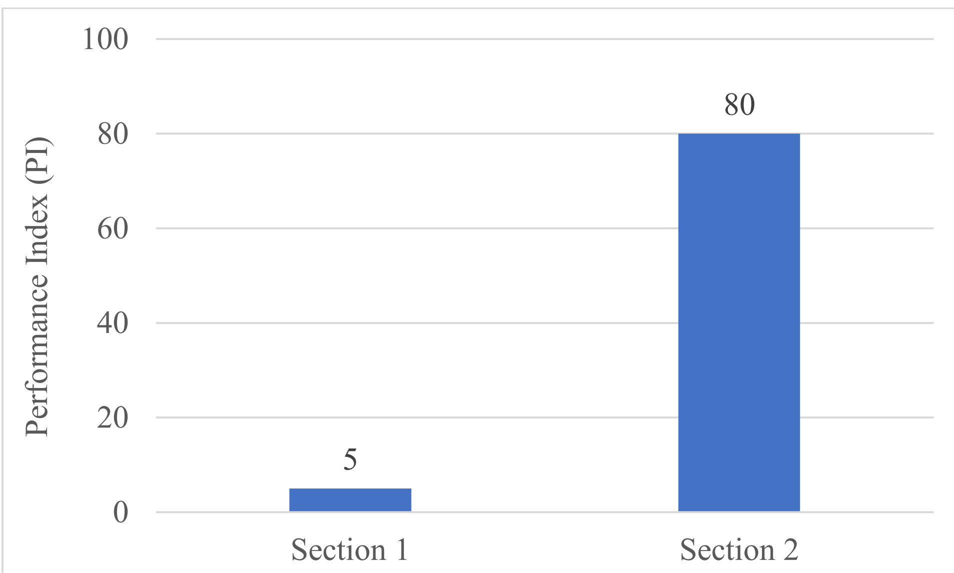


Figure 4.47: Performance Index of the Rural and Urban Segments – Crack Sealed in the Same Year (2012)

CHAPTER 5: EFFECTIVENESS OF CRACK SEALING METHODS

5.1 PERFORMANCE-EFFECTIVENESS

5.1.1 Benefit

The performance-effectiveness of the crack seal was studied in terms of “benefit,” which was derived from the area of the plot between PI and seal age. As discussed in the previous section, such plot was drawn for each crack considered in the field study. Based on the performance trend of all the crack seal project sites considered in this study and practitioners’ opinions on the seal performance, it was decided that a minimum threshold PI of 50 would be reasonable to consider as the failure of the seal. This threshold PI value indicates that 50% of the seal, mainly on the wheel paths, had failed either by one or a combination of typical seal failures (cohesion, adhesion, etc.). The failed seals become ineffective in resisting water infiltration. The pavement structure nearby the failed seal is likely to experience moisture damages and result in secondary distresses. Thus the entire area of the PI vs crack seal age plot was not used, the area up to the threshold PI value was only used for determining the performance-effectiveness of the crack seal. See Figure 5.1. The following subsections discuss the procedures established for determining the benefits for the rout-and-seal and clean-and-seals. As the seasons (especially winters) between the years are usually not identical, for example, the 2018-2019 winter was harsher than 2017-2018, the influence of the seasons on the crack seals differ from year to year. For this reason, benefits were estimated separately, (i) once before the second winter, and (ii) then at the end of the second winter.

5.1.1.1 Rout-and-Seal

Figure 5.1 showed an example of PI vs. crack seal age relationship used for determining the benefit; this particular plot was drawn for Site D (sealed with rout-and-seal) after the first winter. The PI of all the eight cracks in Site D was averaged in this figure. The blue line in this figure represents the PI values measured during the first year of service and the red line shows the forecasted PI beyond the first year of service. As the seal performance data for the newly installed sites was not available until the threshold PI (50), the PI for all these sites had to be forecasted for the period for which data was not available. The trends observed in the relationship of the PI vs. age of crack seal, determined based on the performance data of all the new and old seal projects as shown in Figure 5.2, were used for forecasting the PI. The orange line represents the threshold PI. The area within these lines and the vertical axis marked grey in Figure 5.1, represents the benefit of the crack seals. Such benefit plots were drawn for all the sites after the first winter, and also after the second winter (discussed later). The PI values of all cracks for each site were averaged together to make one representative plot for each site. Figure 5.3 shows the PI vs crack seal age for all rout-and-seal sites; the first two plots ((a) and (b)) are for the data collected before the second winter. The thick black line in Figure 5.3 (a) represents the average value of all sites combined. The forecasted service lives (based on the data until the first winter) for different projects and the respective benefit areas are listed in Table 14. The average benefit for all the rout-and-seal sites was 98. This table also includes the calculated areas for the sites sealed with the clean-and-seal method. Note that Table 14 includes all the sites, including Site A and C, which were treated with micro-surfacing after crack sealant application and not available to monitor the performance. Out of all these sites, only the Sites M, N and O have both rout-and-seal and clean-and-seal methods.

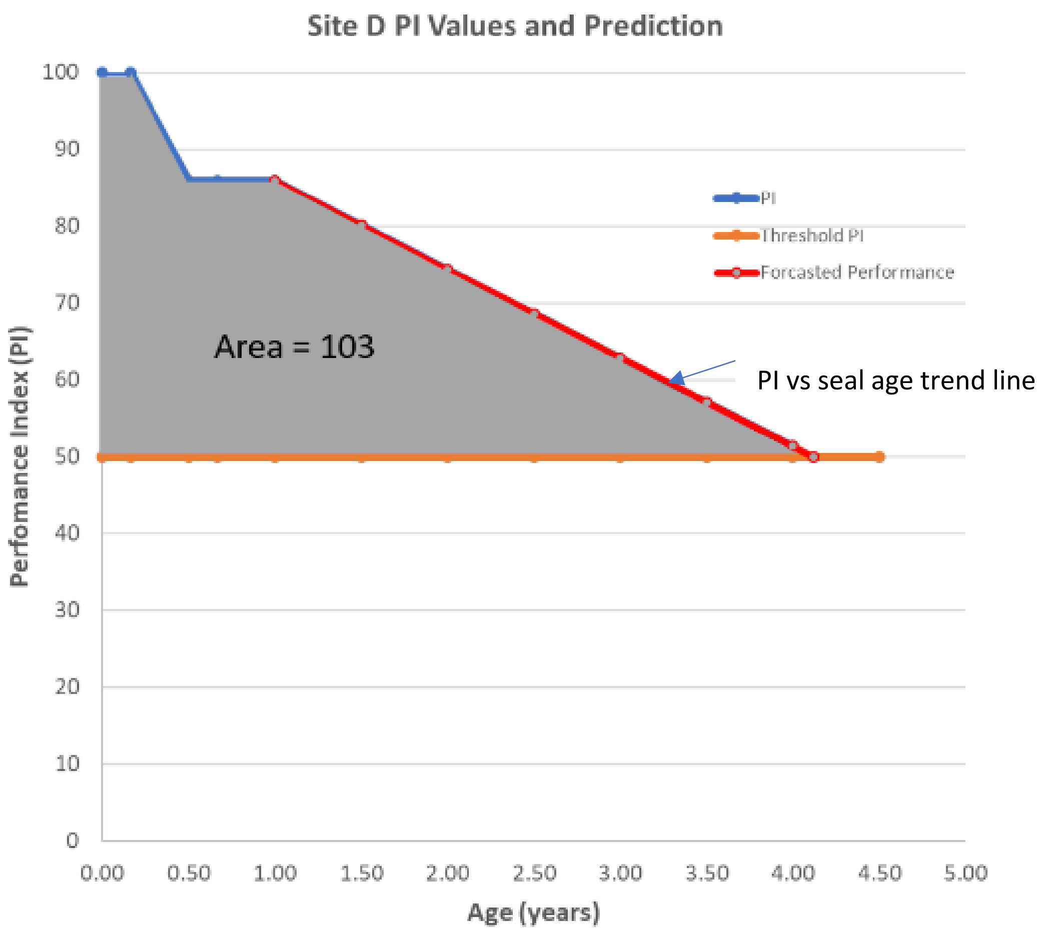


Figure 5.1: PI vs Age of Crack Seal and Benefit Area Calculation (end of first winter)

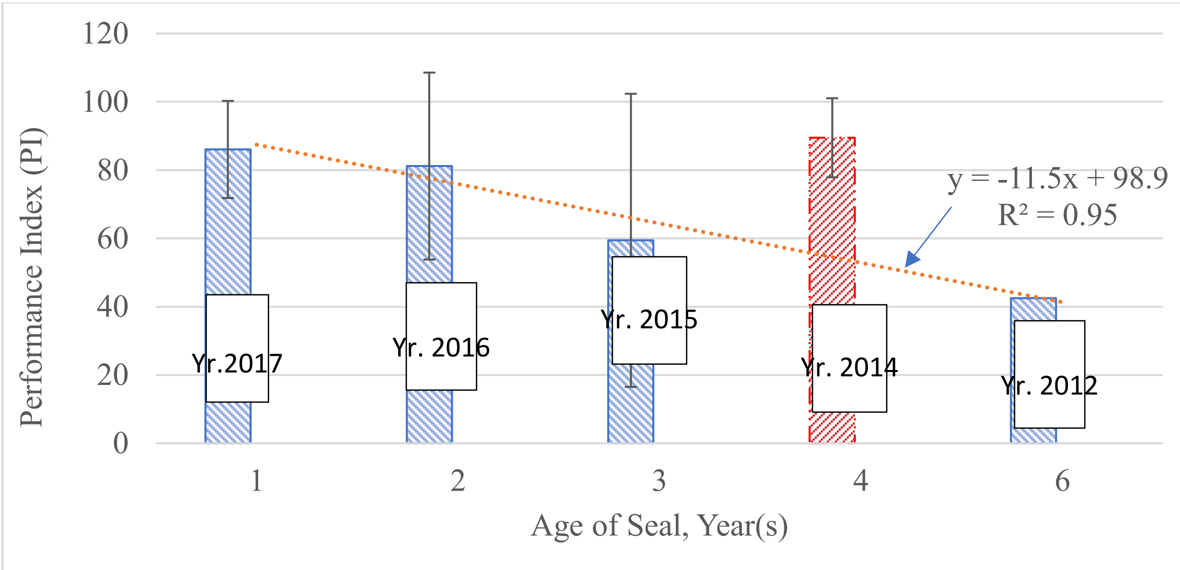


Figure 5.2: Average PI vs. Age of Crack Seal

Table 14: Forecasting of Crack Seal Performance upon First Winter Evaluations

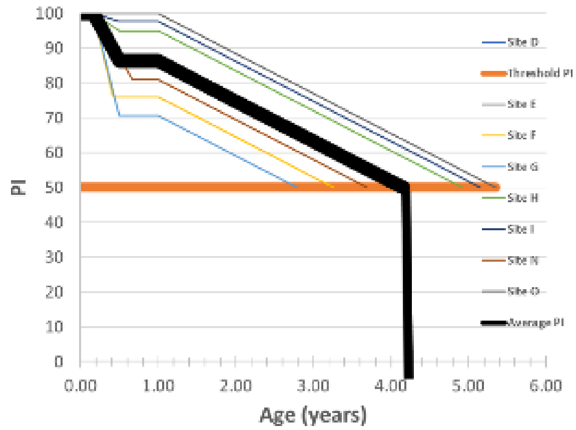
Site ID	Seal Type	Service Life (Age @ 50% Threshold PI) (years)	Benefit Area
A	C-S under micro surface	NA	NA
C	C-S under micro surface	NA	NA
D	R-S	4.12	103
E	R-S	3.98	90
F	R-S	3.26	62
G	R-S	2.79	49

H	R-S	4.92	135
I	R-S	5.15	148
M	R-S	NA	NA
M	C-S	NA	NA
N	R-S	3.69	82
N	C-S	2.72	62
O	R-S	5.35	135
O	C-S	4.31	131
Average Rout-and-Seal Benefit Area			98
Average Clean-and-Seal Benefit Area			86

Note: C-S = Clean-and-seal; R-S = Rout-and-seal; NA = not available

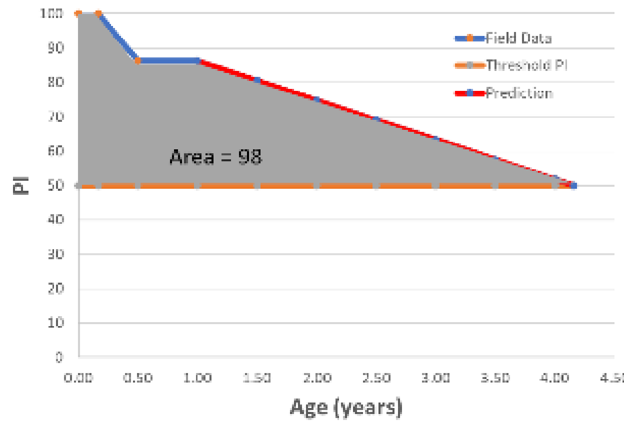
Figure 5.3 (c) and (d) shows the PI vs. crack seal age for all the data collected for all rout-and-seal sites until the second winter (including early spring). The figures indicate that the benefit and forecasted service lives did not follow the same trend as anticipated before collecting the data in the second winter. The cracks experienced larger failure than anticipated and expected to last shorter than forecasted; the severely cold temperature during the 2018-2019 winter could have played a great role in this. The thick black line in Figure 5.3 (c) represents the average value of all sites combined.

Table 15 shows the re-calculated service lives and benefits based on the data collected after the second winter. The average benefit was found as 75.

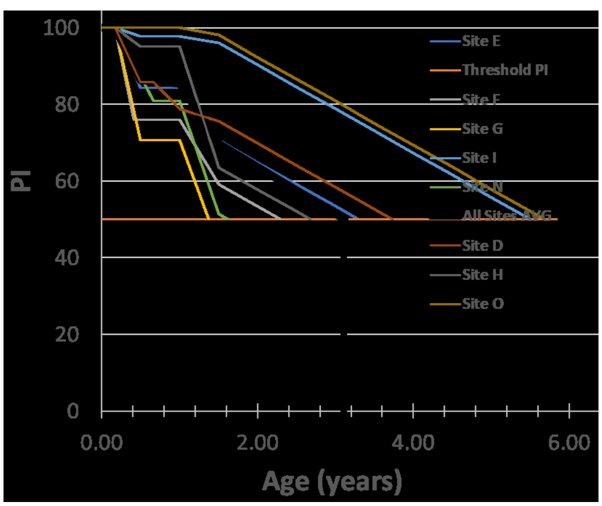


(a) All Rout-and-seal Sites

(First Winter)

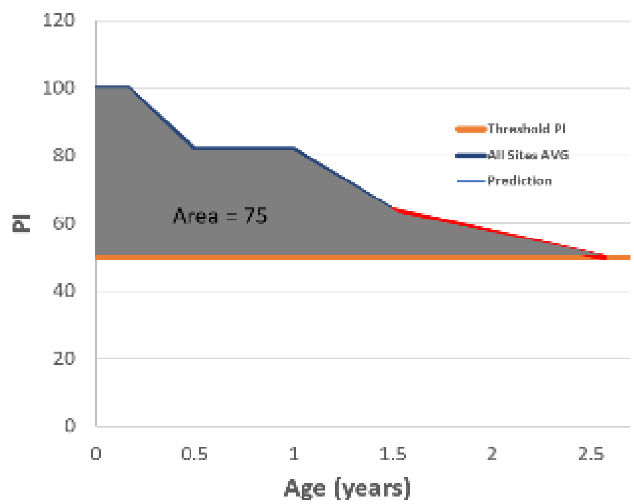


(b) Avg. Benefit of all Rout-and-seal Sites (First Winter)



(c) All Sites (Rout-and-seal)

(Second Winter)



(d) Avg. Benefit of all Rout-and-seal Sites (Second Winter)

Figure 5.3: Performance Evaluations and Average Benefit Area of Rout-and-Seal Projects

Table 15: Forecasting of Crack Seal Performance after Second Winter Evaluations

Site ID	Seal Type	Service Life (Age @ 50% Threshold PI) (years)	Benefit Area
A	C-S under micro surface	NA	NA
C	C-S under micro surface	NA	NA
D	R-S	NA	79
E	R-S	3.29	67
F	R-S	2.30	46
G	R-S	1.37	34
H	R-S	NA	67
I	R-S	5.73	177
M	R-S	NA	8
M	C-S	NA	6
N	R-S	1.62	55
N	C-S	2.22	59
O	R-S	NA	167
O	C-S	NA	103

Average Rout-and-Seal Benefit Area	78
Average Clean-and-Seal Benefit Area	72

Table 16 provides a list of the age of seal with respect to different PI values of the first winter evaluations, determined by using the correlation shown in Figure 5.2. Based on a 50% threshold PI, the service life of rout-and-seal is roughly four years. It is noted that the age corresponding to the 50% threshold PI was referred to as the service life. Figure 5.4 shows the probability density function for the service life for the rout-and-seal projects. This figure can estimate the service life of the projects at a different level of reliabilities. Table 17 shows that the average service life of rout-and-seal is 4.2 years with a reliability of 50% and it is 2.3 years with a reliability of 97.5%. Note that the benefit and the life cycle cost analysis were performed for the service life with a 50% reliability.

Table 16: Estimated PI vs Service Life for Rout-and-Seal after First Winter

PI	Age of Seal (year)
90	0.8
80	1.6
70	2.5
60	3.4
50	4.2
40	5.1
30	6.0
20	6.8
10	7.7

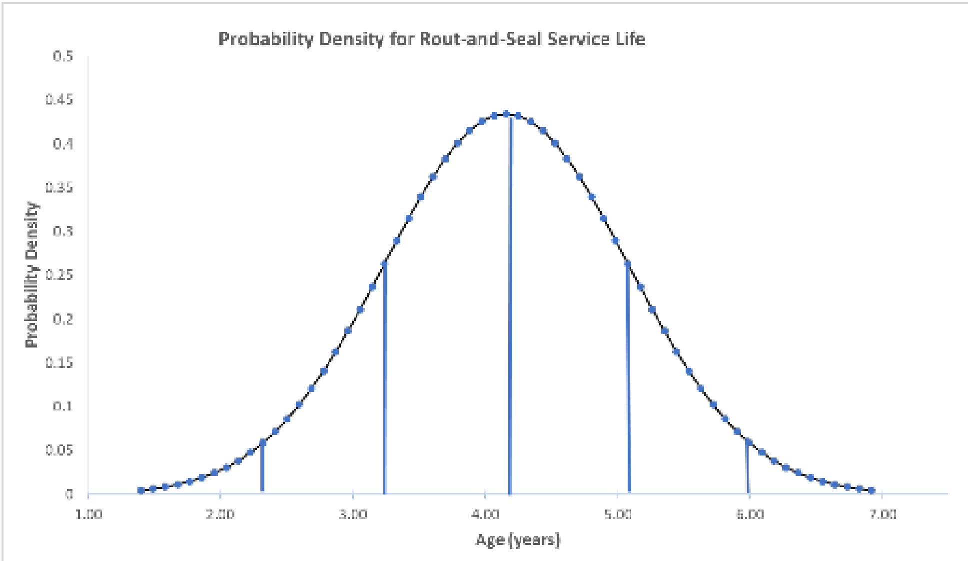


Figure 5.4: Probability Distribution of Rout-and-Seal Service life

Table 17: Rout-and-Seal Service Life and Reliability after First Winter

Service life	Reliability
2.3	97.5%
3.2	84%
4.2	**50%**
5.0	16%
6	2.5%

Upon documenting seal performance during the second winter, a new probability density function was created. This new function shows that seal performance, as stated earlier, deteriorated more quickly on these sites that had been anticipated based on the correlation of older crack seal sites. In order to create this curve, sites I and O had to be excluded due to their much higher PI values. These high PI values are associated with the tight crack spacing and low volumes of traffic seen at these sites, and they were considered as the outlier as a result.

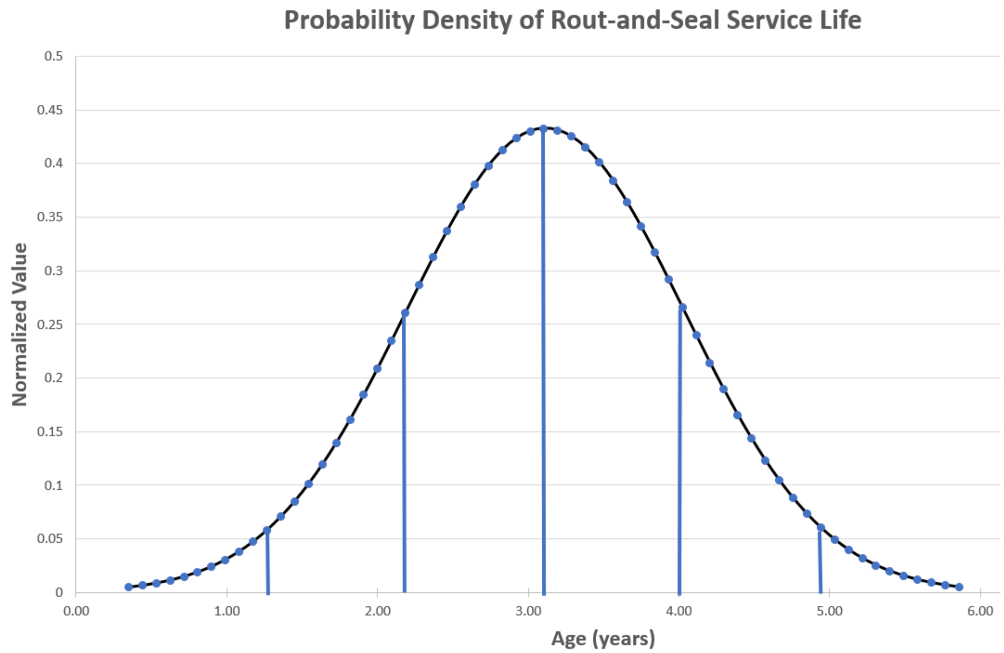


Figure 5.5: Probability Distribution of Rout-and-Seal Service Life after Second Winter Analysis

Table 18: Rout-and-Seal Service Life and Reliability after Second Winter

Service life	Reliability
1.27	97.5%
2.19	84%
3.10	**50%**
4.02	16%
4.94	2.5%

5.1.1.2 Clean-and-Seal

Due to a lack of sufficient data for the clean-and-seal method, the PI vs. age of seal trend line for this method was obtained indirectly by adjusting the trend line developed for the rout-and-seal method (Figure 5.2). The main assumption of this adjustment was that the clean-and-seal method performs about one year less than the rout-and-seal method as suggested by many previous studies (Table 21). Figure 5.6 shows a schematic indicating the adjustment made for the clean-and-seal method. The 'corrected area,' shaded in grey, refers the area for the clean-and-seal benefit area. The 'uncorrected area,' shaded in red, refers to the difference in the benefits area between the rout-and-seal and clean-and-seal methods. For this particular example, the clean-and-seal method provides 21.6% less benefit than what is provided by the rout-and-seal method.

Using the previously mentioned procedure for the clean-and-seal method, the PI vs age of seal areas were plotted for the sites that have PI data (8 sites) for the data until before the second winter, excluding the Sites A, C and M. Figure 5.7 shows the PI vs age of seal for all these eight sites. The wider black line represents the average value of all eight sites combined. Figure 5.8 shows the average benefit area for all the eight sites combined, with a threshold PI of 50; the average service life for the clean-and-seal method is 3.12 years with a benefit area equal to 86.

Figure 5.9 shows the probability density function for the service life for the clean-and-seal projects. Table 19 shows that the average service life of clean-and-seal is 3.2 years with a reliability of 50% and it is 1.3 years with a reliability of 97.5%.

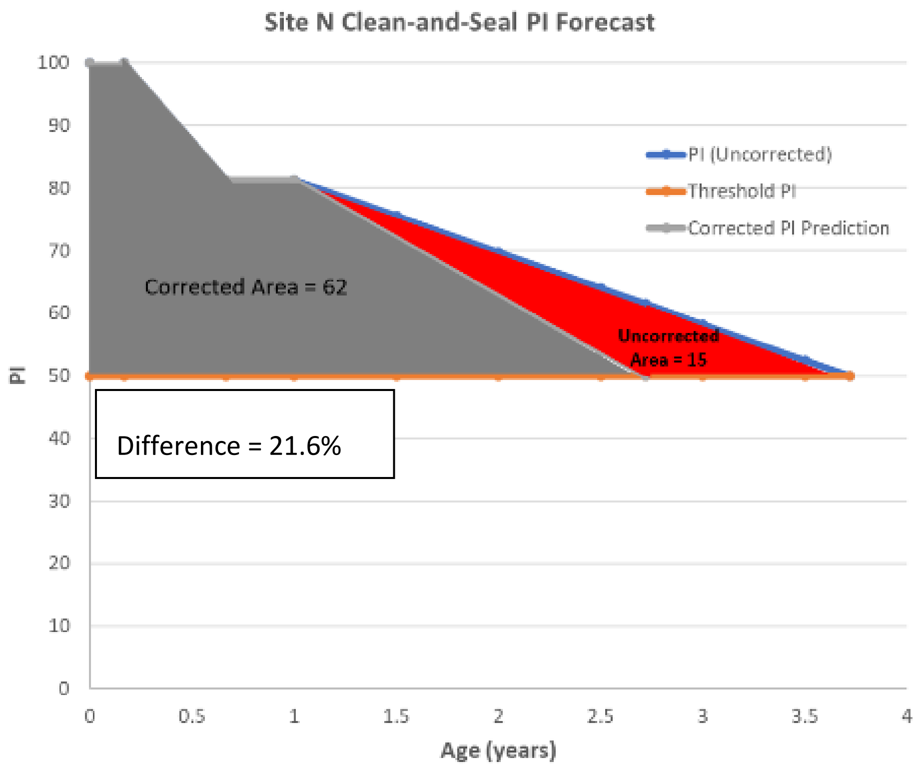


Figure 5.6: Clean-and-Seal Benefit Area Determination (end of the first winter)

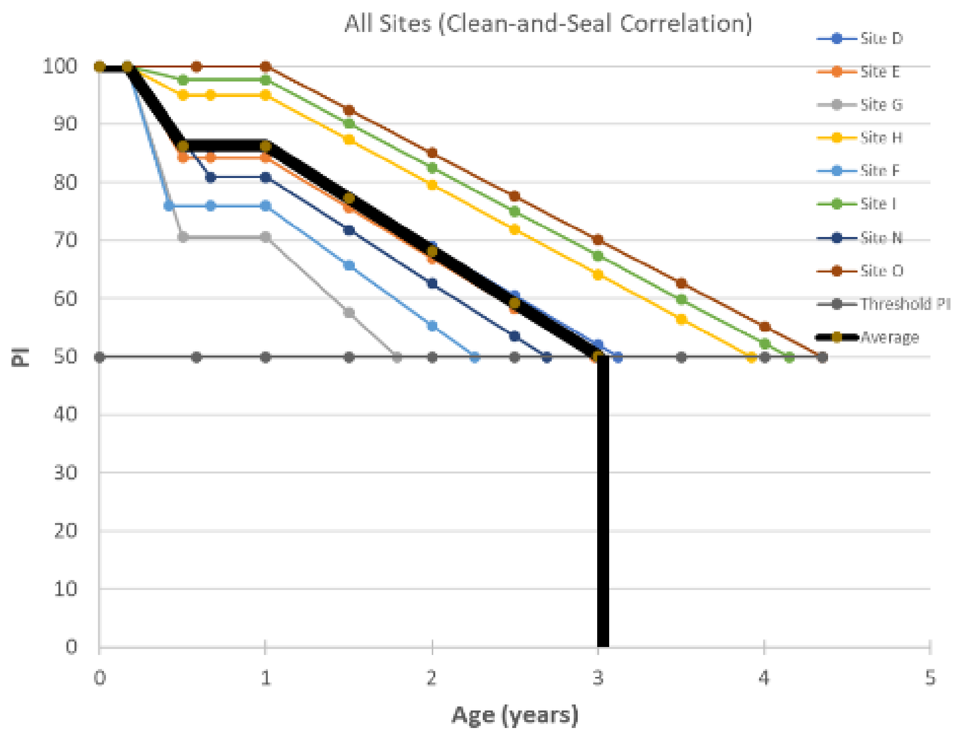


Figure 5.7: Service Life of Clean-and-Seal method for Different Sites after First Winter

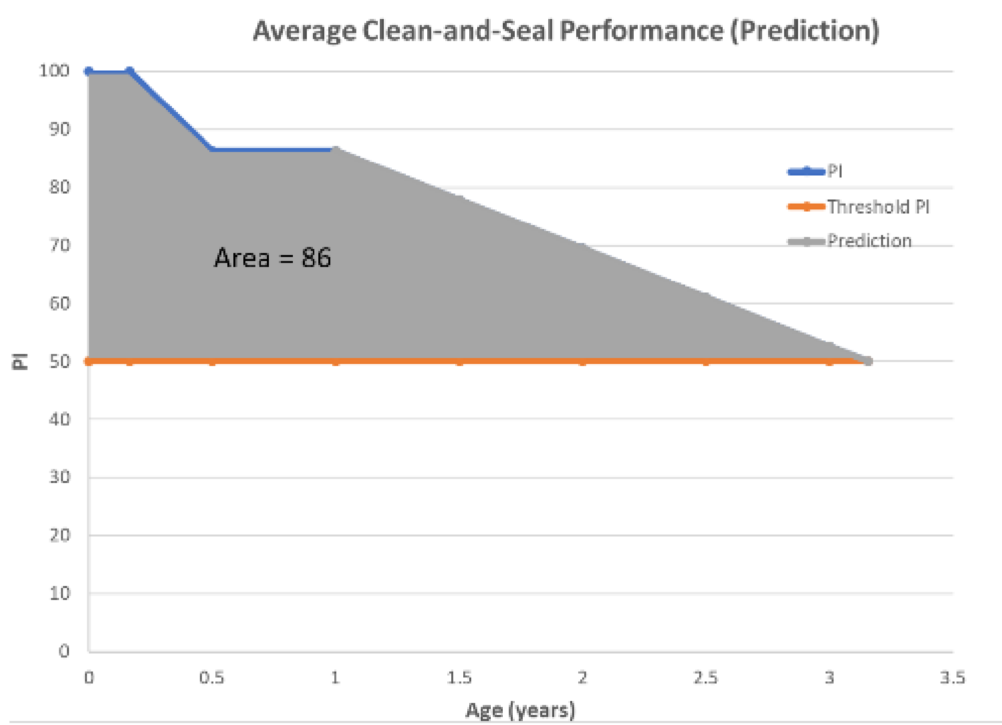


Figure 5.8: Average Benefit Area for Clean-and-Seal method (end of the first winter)

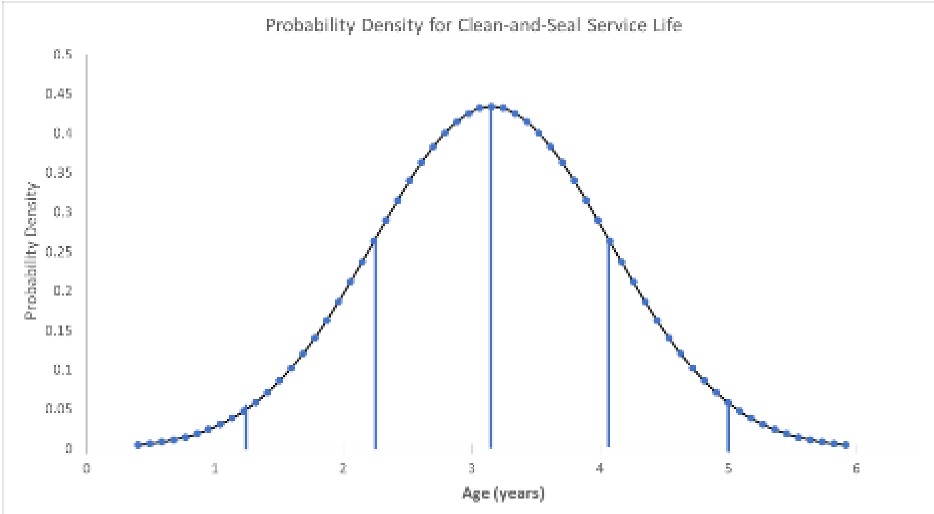


Figure 5.9: Probability Density for Clean-and-Seal Service Life after First Winer Analysis

Table 19: Clean-and-Seal Service Life and Reliability after First Winter

Service Life	Reliability
1.3	97.5%
2.4	84%
3.2	**50%**
4.1	16%
5	2.5%

By making the assumption that a clean-and-seal will last one year less than rout-and-seal to meet its threshold performance index, Figure 5.10 is drawn to determine the benefit for the clean-and-seal method including the data collected after the second winter. The expected service life probabilities for clean-and-seal, based on the second winter data, is shown in Table 20 below. Based on the second winter data, it appears that the service life of the clean-and-seal method could be approximately 2 years with 50% reliability.

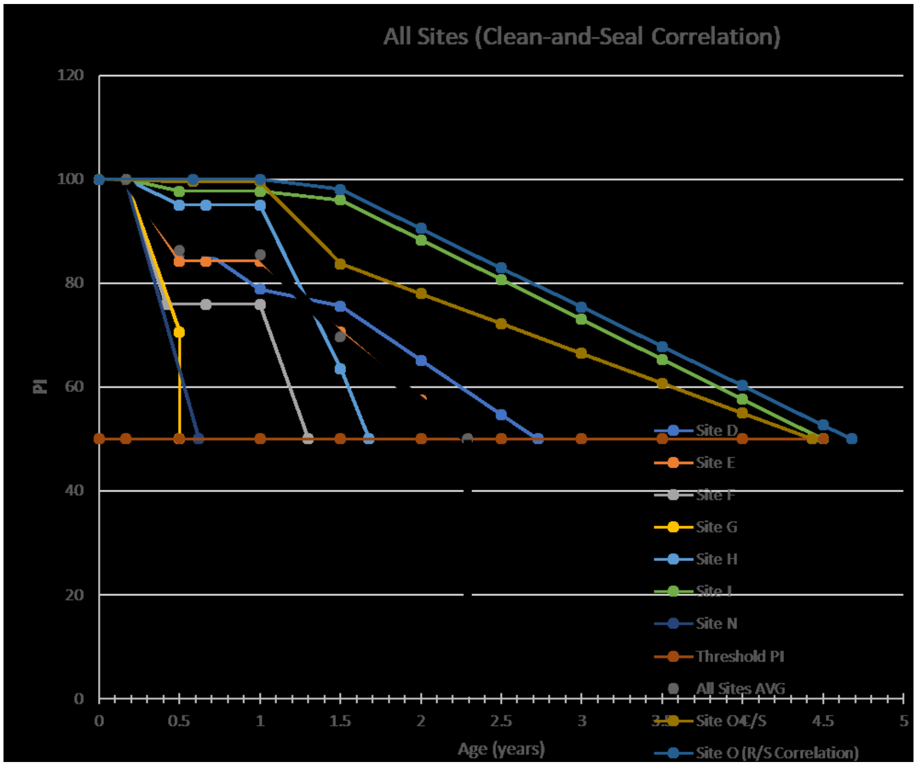


Figure 5.10: Service Life of Clean-and-Seal method for Different Sites after the Second Winter

Table 20: Clean-and-Seal Service Life and Reliability after Second Winter

Service life	Reliability
0.3	97.5%
1.2	84%
2.1	**50%**
3.1	16%
3.9	2.5%

5.1.1.3 Summary of Performance-effectiveness

Based on the second winter crack seal performance trend, it can be stated that the second winter has caused a significant amount of failures of the crack seals irrespective of the sealing method. The severely cold 2018-2019 winter has expanded many cracks beyond the typical winter average crack widths, which stretched sealants beyond their allowable strains. Also, in many sites, new thermal cracks have developed in between the previously recorded cracks (e.g., Site M). As this kind of aggressive winter may not be typical, it is assumed that the service lives of crack seal methods determined based on the first winter data from the newly installed crack seals (Phase 3) and old crack seal data (Phase 4, includes data of the seals that experienced 1 to 6 winters) may be considered as more reasonable as opposed to what was determined based on the second winter data alone (unusual winter). Therefore, the average service life for the rout-and-seal and clean-and-seal are finalized as four years and three years, respectively. The life-cycle cost analysis in this study was thereby performed using the above-mentioned service lives.

The suggested average service lives for the two methods are also comparable with the service lives obtained in other states of similar climate to Minnesota (Figure 5.11 and Table 21), including Al Quadi et al. (2017) study that compared the performances of rout-and-seal and clean-and-seal methods. Note that the 6-year period corresponding to the MnDOT construction log (Figure 5.11) is actually the service period, not necessarily the service life. This only means that MnDOT usually applied a surface treatment on the pavements on average 6-year after the crack sealant installation.

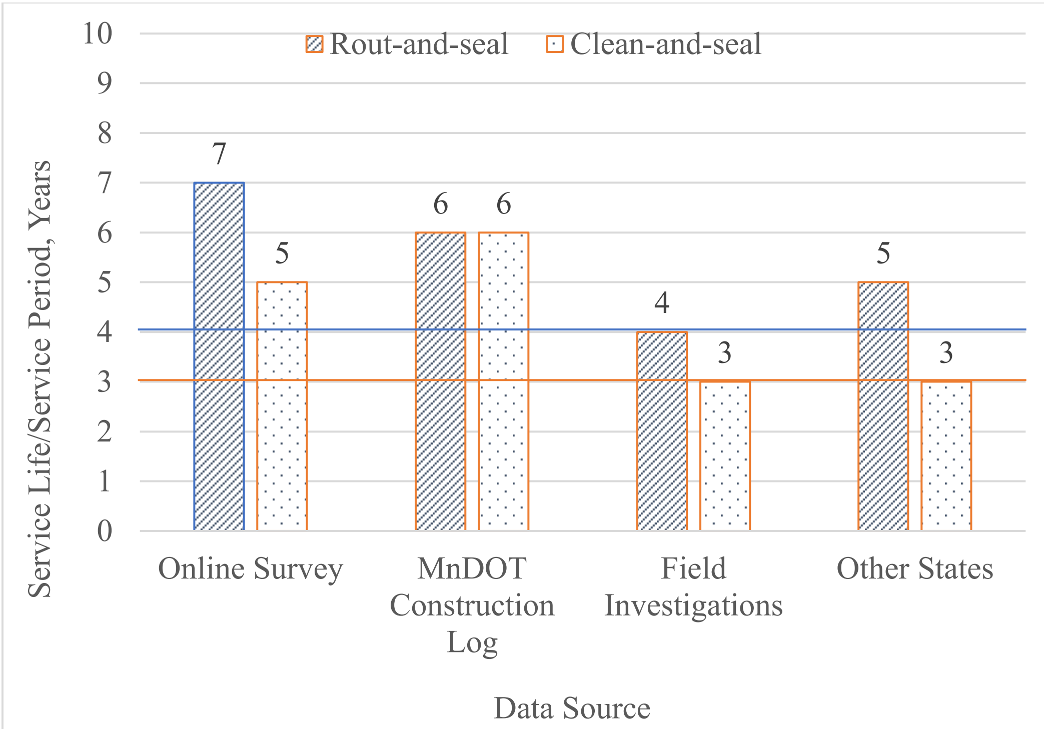


Figure 5.11: Service Life/ Service Period of Crack Seals from Different Sources

Table 21: Service Life of Crack Seals Observed in Different USA States and Canadian Provinces

Method / State or Province	Crack Sealing/ Rout-and-Seal	Crack Filling/ Clean-and-Seal
Minnesota (MnDOT, 2018a)	2 to 4 yrs	1 to 3 yrs
Illinois (IL DOT, 2010)	2 to 8 yrs	2 to 4 yrs
Colorado (Galehouse, 2004)	2 to 4 yrs (based on traffic levels)	2 to 4 yrs (based on traffic levels)
Virginia (Al-Quadi et al., 2017)	2-3 yrs	1-2 yrs
Ontario, Ca (OHMPA, 2004)	3 to 5 yrs	N/A
Alberta, Ca (AL Trans, 2003)	5 to 8 yrs	1 to 3 yrs

Average Range	**2-8 yrs**	**1-4 yrs**
Average	**5 yrs**	**3 yrs**

5.2 COST-EFFECTIVENESS

Cost-effectiveness was established by determining the benefit to cost (B/C) ratio of each crack sealing method. The B/C ratio analysis was initially performed for the crack sealing treatment cost alone, then for all the costs incurred during the life cycle (analysis period) of the pavement. The average benefit determined in the previous subsection was considered as the "benefit" in the B/C ratio analysis and it is noted here that the "benefit" in this analysis is not a dollar amount. The following subsection discusses different components of the B/C analysis performed in this study.

5.2.1 Unit Cost of Crack Sealing

The unit cost of rout-and-seal crack sealing was obtained from the Life-Cycle Cost Analysis (LCCA) Spreadsheet available at the MnDOT website for the MnDOT District-1. Since the MnDOT's LCCA Spreadsheet does not provide unit cost for specific crack sealing treatment type, the given crack treatment cost was assumed as the unit cost of rout-and-seal treatment. The cost of clean-and-seal treatment was then determined using some representative bid letting abstracts from the MnDOT website. These bid letting abstracts included both rout-and-seal and clean-and-seal methods. Using the unit prices available in those bid letting abstracts, the year of the bid, MnDOT's suggested discounted rate, and the present year (2018) unit costs were calculated for the all the bids. The following equation was used to determine the older year unit cost to the present year (2018) unit cost:

Present cost, $C_p = C_u * (1+i)^n$ (5)

Where,

C_u=Unit Cost in the year of treatment

i= discount rate (1.22%, collected from MnDOT District-1's LCCA spreadsheet)

n = the time in years until 2018

Table 22 shows the details of the present year unit cost along with the other information used. The present year's unit costs for all the rout-and-seal and clean-and-seal projects were then averaged, separately. The average cost for the rout-and-seal and clean-and-seal methods were $101.3 and $55.4, per road station (RDST). The ratio of the average costs of rout-and-seal to the clean-and-seal unit was found to be 1.8. This ratio was used to determine the final unit cost for the clean-and-seal method. Table 23 provides the cost of the crack sealing treatment per lane mile for both rout-and-seal and clean-and-seal methods.

Table 22: Unit Cost of Crack Sealing Treatments Obtained from Previous Bid Letting Abstracts

Project Year	SP #	Unit	Unit Price ($)	n (up to 2018)	Discount Rate, i	Present Cost ($)
Rout-and-seal						
2006	4508-26	RDST	51	12	0.0122	59.0
2009	8825-336	RDST	159	9	0.0122	177.3
2006	8827-68	RDST	65	12	0.0122	75.2
2007	3404-54	RDST	82.16	11	0.0122	93.9
Average Unit Cost per Road Station (RDST), $						**101.3**
Clean-and-seal						
2007	2001-33	RDST	35	11	0.0122	40.0
2008	2801-86	RDST	62.8	10	0.0122	70.9
Average Unit Cost per Road Station (RDST), $						**55.4**
Cost ratio: Rout-and-seal to Clean-and-seal (=101.3/55.4)						**1.8**

Table 23: Crack Sealing Unit Cost per Lane Mile

	Length (Mile)	Width (ft)	Quantity per lane mile	Unit	Unit Price ($)	Total Price ($)
Rout-and-seal	1	12	7040	SY	0.46	3,238.4
Clean-and-seal	1	12	7040	SY	0.26	1799.1

5.2.2 Pavement Life-Cycle Cost (LCC)

5.2.2.1 Initial Construction Cost

In order to determine the initial construction cost, a typical and stout pavement cross-section was selected from the MnDOT's pavement design guidelines (MnDOT, 2018b). Figure 5.12 and Figure 5.13 show the cross-section and layer thickness details of that typical section. Three pavement configurations, such as one New HMA and two HMA Overlays with 13 and 20 years of design lives, were considered for this analysis. Different milling and wearing course depths were used for HMA Overlay with varying design lives. Table 24 to Table 26 show the details of the different items and their respective initial construction costs for the three configurations. The quantities of each of these items were determined using MnDOT District-1's LCCA spreadsheet.

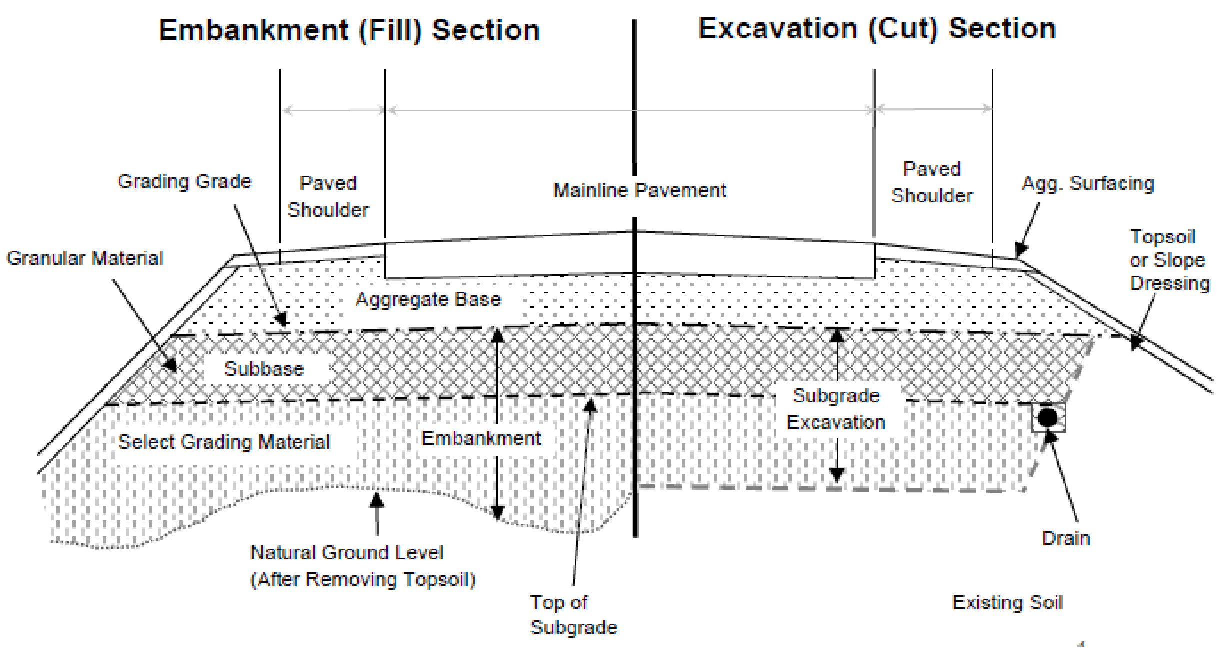
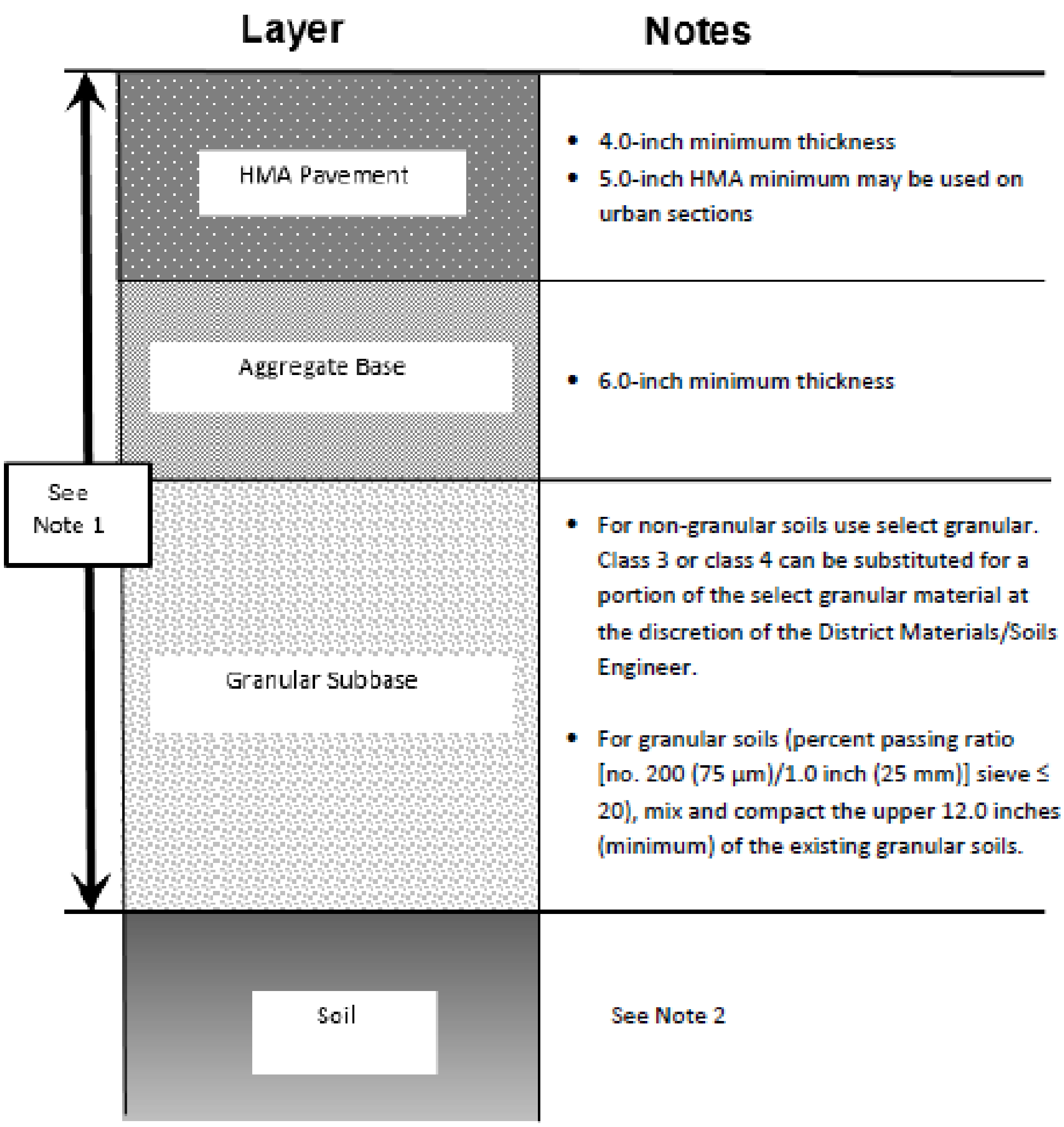


Figure 5.12: A Typical MnDOT Pavement Cross Section (after MnDOT, 2018b)



NOTE 1 For non-granular soils, the minimum pavement structure (i.e. pavement, aggregate base, and subbase) thickness required is:

- 30.0 inches for 20-year BESALs ≤ 7 million
- 36.0 inches for 20-year BESALs > 7 million

NOTE 2 Any construction beneath the typicals shown above shall be at the discretion of the District Materials/Soils Engineer.

Figure 5.13: Typical MnDOT Pavement Structure Thickness Selection Guideline (after MnDOT, 2018b)

Table 24: Initial Construction Cost Per Lane-Mile, New HMA, Design Life = 20 Years

	Depth (in)	Width (ft)	RDST	Quantity per mile	Unit	Unit Price ($)	Total Price ($)
Subgrade Preparation (RDST)			53	53	RDST	102.35	5,424
Select Granular Embankment MOD 7% (CV)	14	12		2737.8	CY	21.15	57,905
Aggregate Base (CV) Class 5	10	12		1955.6	CY	31.41	61,425
Non-Wearing Course Mixture (4, B)	4	12		1591	TON-B	62.75	99,835
Wearing Course Mixture (4,C)	4	12		1591	TON-B	82.33	130,994
Grand Total							**355,584**

Table 25: Initial Construction Cost Per Lane-Mile, HMA Overlay, Design Life = 13 Years

	Depth (in)	Width (ft)	Quantity per mile	Unit	Unit Price ($)	Total Price ($)
Mill Bituminous Surface	1.5	12	7040	SY	0.81	5,702

Wearing Course Mixture (4, B)	3	12	1392.2	TON-B	77.58	92,571
Grand Total						**98,274**

Table 26: Initial Construction Cost Per Lane-Mile, HMA Overlay, Design Life = 20 Years

	Depth (in)	**Width (ft)**	**Quantity per mile**	**Unit**	**Unit Price ($)**	**Total Price ($)**
Mill Bituminous Surface	2	12	7040	SY	1.22	8,589
Wearing Course Mixture (4,B)	4.5	12	1789.9	TON-B	72.85	130,394
Grand Total						**139,983**

5.2.2.2 Maintenance and Rehabilitation Activities and Costs

The maintenance and rehabilitation activity schedules were initially collected from the MnDOT Pavement design manual (MnDOT, 2018b) for four different cases as follows: (i) Case 1: New HMA with 20-year design life and 35-year analysis period; (ii) Case 2: New HMA with 20- year design life and 50-year analysis period; (iii) Case 3: HMA Overlay with 13-year design life and 35-year analysis period; and (iv) Case 4: HMA Overlay with 20-year design life and 35-year analysis period. These schedules consider a four-year service period between crack sealant installation and the follow-up surface treatment, which is similar to the service life of the rout-and-seal treatment, determined in the previous section of this report. The service life of clean-and-seal was determined as three years. As the clean-and-seal performs one year less than four years, a re-sealing activity was considered for the remaining one-year service life; it was assumed that 30% of the failed clean-and-seal seals would be re-sealed after three years of the service period.

The relevant unit costs of maintenance and rehabilitation activities (other than sealing costs) were obtained from the MnDOT District-1's LCCA spreadsheet. The Net Present Values (NPV) of different items were calculated using the following equation:

$$\text{Net Present Value (NPV)} = C_{in} + \sum_{t=1}^{N} \frac{C_{at}}{(1+i)^t} \qquad (6)$$

Where,

C_{in} = initial cost of construction

t = the time in future in years

N = the number of years in the analysis period

C_{at} = the cost of activity t years in the future

i = the annual rate of interest in decimals (1.22%, collected from the MnDOT District-1's LCCA spreadsheet)

Table 27 to Table 30 show the details of maintenance and rehabilitation schedules and the corresponding initial and net present value cost information for different cases considered. It can be seen that the life cycle cost for the rout-and-seal method is slightly higher than the clean-and-seal method for all the cases.

Table 27: Example LCCA per lane mile for a Typical New HMA with 20 years of design life and 35 years Analysis Period

	Rout-and-seal			Clean-and-seal		
	Initial Cost ($)	**Age, Year**	**NPV ($)**	**Initial Cost ($)**	**Age**	**NPV ($)**
Initial Construction	355,584	0	355,584	355,584	0	355,584
Crack Treatment	3,238	8	2,939	1,799	8	1,633
Crack Re-sealing	-	None	-	600	11	525
Surface Treatment (UTBWC)	50,688	12	43,824	50,688	12	43,824
Mill 1.5" and HMA Overlay 3.5" (9.5 Wearing - 4,B)	123,739	20	97,091	123,739	20	97,091
Crack Treatment	3,238	23	2,450	1,799	23	1,361

Crack Re-sealing	-	-	-	600	26	438
Surface Treatment (UTBWC)	50,688	27	36,535	50,688	27	36,535
End of Analysis period (2/17 Remaining Life)	14,557	35	9,523	14,557	35	9,523
Life Cycle Cost			**$ 528,900**			**$ 527,467**

Table 28: Example LCCA per lane mile for a Typical New HMA with 20 years of design life and 50 years Analysis Period

	Rout-and-seal			**Clean-and-seal**		
	Initial Cost ($)	**Age, Year**	**NPV ($)**	**Initial Cost ($)**	**Age, Year**	**NPV ($)**
Initial Construction	355,584	0	355,584	355,584	0	355,584
Crack Treatment	3,238	8	2,939	1,799	8	1,633
Crack Re-sealing	-	-	-	600	11	525
Surface Treatment (UTBWC)	50,688	12	43,824	50,688	12	43,824
Mill 1.5" and HMA Overlay 3.5" (9.5 Wearing - 4,B)	123,739	20	97,091	123,739	20	97,091
Crack Treatment	3,238	23	2,450	1,799	23	1,361
Crack Re-sealing	-	-	-	600	26	438

Surface Treatment (UTBWC)	50,688	27	36,535	50,688	27	36,535
Mill 1.5" and HMA Overlay 3.5" (9.5 Wearing - 4,B)	123,739	37	79,004	123,739	37	79,004
Crack Treatment	3,238	40	1,994	1,799	40	1,108
Crack Re-sealing	-	-	-	600	43	356
Surface Treatment (Chip Seal)	15,136	44	8,878	15,136	44	8,878
End of Analysis period (4/17 Remaining Life)	29,115	50	15,878	29,115	50	15,878
Life Cycle Cost			**$ 612,421**			**$ 610,458**

Table 29: Example LCCA per lane mile for a Typical HMA Overlay with 13 years design life and 35 years Analysis Period

	Rout-and-seal			Clean-and-seal		
	Initial Cost ($)	Age, Year	NPV ($)	Initial Cost ($)	Age, Year	NPV ($)
Mill 1.5" and HMA Overlay 3.5" (9.5 Wearing - 4,B)	98,274	0	98,274	98,274	0	98,274
Crack Treatment	3,238	3	3,123	1,799	3	1,735
Crack Re-sealing	-	-	-	600	6	558
Surface Treatment (Chip Seal)	15,136	7	13,904	15,136	7	13,904
Mill 1.5" and HMA Overlay 3.5" (9.5 Wearing - 4,B)	98,274	13	83,941	98,274	13	83,941
Crack Treatment	3,238	16	2,667	1,799	16	1,482
Crack Re-sealing	-	-	-	600	19	476
Surface Treatment (Chip Seal)	15,136	20	11,876	15,136	20	11,876
Mill 1.5" and HMA Overlay 3.5" (9.5 Wearing - 4,B)	98,274	25	72,574	98,274	25	72,574
Crack Treatment	3,238	28	2,306	1,799	28	1,281

Crack Re-sealing	-	-	-	600	31	412
Surface Treatment (Chip Seal)	15,136	32	10,268	15,136	32	10,268
End of Analysis period (3/17 Remaining Life)	17,342	35	11,345	17,342	35	11,345
Life Cycle Cost			**$ 287,588**			**$ 285,436**

Table 30: Example LCCA per lane mile for a Typical HMA Overlay with 20 years design life and 35 years Analysis Period

	Rout-and-seal			**Clean-and-seal**		
	Initial Cost ($)	**Age, Year**	**NPV ($)**	**Initial Cost ($)**	**Age, Year**	**NPV ($)**
Mill 2" and HMA Overlay 4.5" (9.5 Wearing - 4,B)	138,983	0	138,983	138,983	0	138,983
Crack Treatment	3,238	3	3,123	1,799	3	1,735
Crack Re-sealing	-	-	-	600	6	558

Surface Treatment (UTBWC)	50,688	7	46,563	50,688	7	46,563
Mill 2" and HMA Overlay 4.5" (9.5 Wearing - 4,B)	138,983	20	109,052	138,983	20	109,052
Crack Treatment	3,238	23	2,450	1,799	23	1,361
Crack Re-sealing	-	-	-	600	26	438
Surface Treatment (UTBWC)	50,688	27	36,535	50,688	27	36,535
End of Analysis period (5/17 Remaining Life)	40,877	35	26,740	40,877	35	26,740
Life Cycle Cost			**$ 309,967**			**$ 308,485**

5.3 THE BENEFIT TO COST (B/C) RATIO

The performance-effectiveness and cost-effectiveness were determined using the benefit to cost ratio. First, the 'benefit to *treatment-cost* ratio' of the two sealing methods was compared. It can be seen in

Table 31 and Figure 5.14 that the clean-and-seal method provides greater 'benefit to *treatment-cost* ratio.' This indicates that if the only short-term benefit is considered, then the clean-and-seal may be more cost-effective than its counterparts. Second, the 'benefit to *life-cycle-cost* ratio' of the two sealing methods was compared. As shown in

Table 32 and Figure 5.15, it can be seen that when 'benefit to *life-cycle-cost* ratio' was compared between the two sealing methods, the rout-and-seal method provides slightly more cost-effectiveness for all the four different cases considered in this study. However, as the difference is very small, it would be worth to look at other decision factors for recommending the crack seal method for a specific job.

Table 31: Benefit/Treatment Cost Ratio of Rout-and-Seal and Clean-and-Seal Methods

	Benefit	Cost per lane-mile (1,000 $)	B/C ratio
Rout-and-seal	98	$ 3.238	30.26
Clean-and-seal	86	$ 1.799	47.80

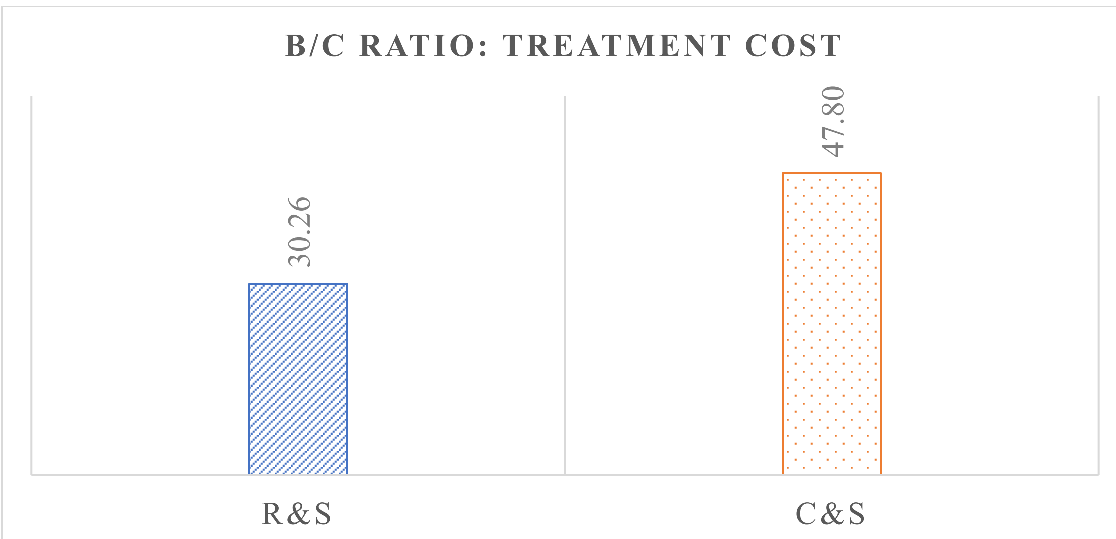


Figure 5.14: Benefit/Treatment Cost Ratio of Rout-and-Seal and Clean-and-Seal (Note- 'benefit' here is not in terms of the dollar, so B/C ratio shall not be compared with unity (one))

Table 32: Benefit/ Life-Cycle-Cost Ratio of Rout-and-Seal and Clean-and-Seal Methods

	LCC		Benefit		B/C(1000$)	
Case	**R&S**	**C&S**	**R&S**	**C&S**	**R&S**	**C&S**
Case 1	$528,900	$527,467	98	86	0.185	0.1630

Case 2	$612,421	$610,458	98	86	0.160	0.1409
Case 3	$287,588	$285,436	98	86	0.341	0.3013
Case 4	$309,967	$308,485	98	86	0.316	0.2788

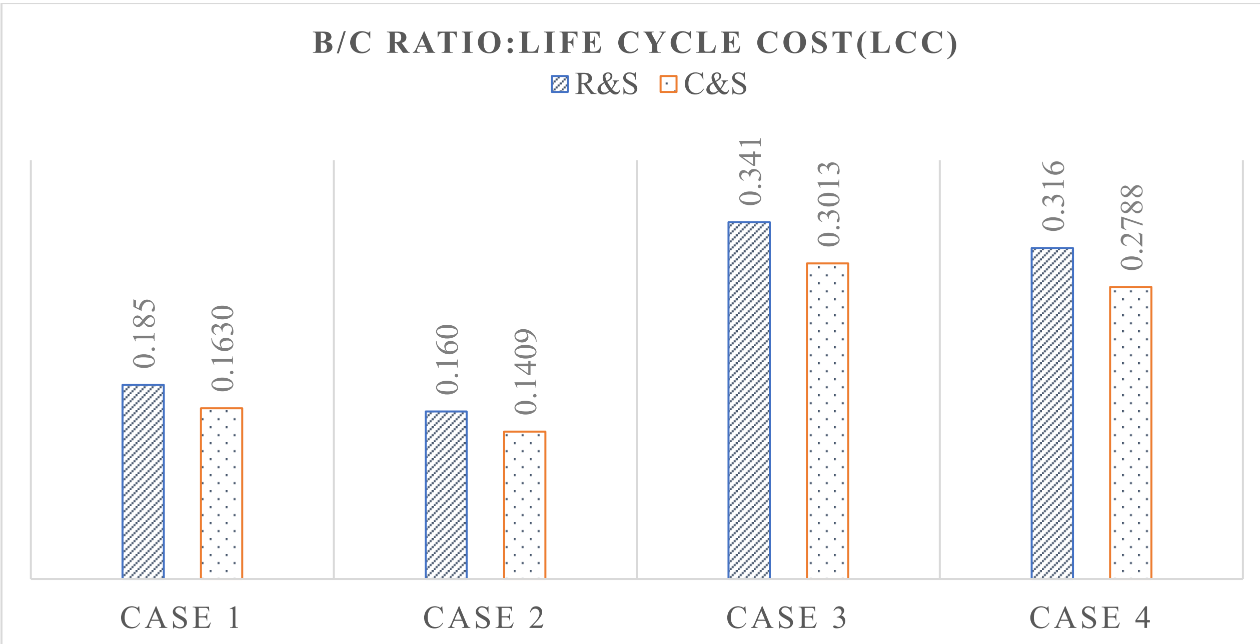


Figure 5.15: Benefit/Cost Ratio for Rout-and-Seal and Clean-and-Seal for Different Cases

CHAPTER 6: DRAFT RECOMMENDATION FOR THE SELECTION OF APPROPRIATE CRACK SEALING METHOD

In this section, a draft recommendation was developed for selecting the appropriate crack sealing method for asphalt pavement cracks. Easy-to-use decision trees have been developed to aid in deciding whether to seal with clean-and-seal or rout-and-seal method based on many relevant variables, such as crack severity, pavement type and age, traffic level, and subgrade soil type.

6.1 VARIABLES

6.1.1 Crack Severity and Crack Width

The crack severity largely influences the selection of the crack sealing method. The severity of crack is defined with respect to the width of the crack (CW). While either of the rout-and-seal or clean-and-seal method may be implemented on the low and moderate severity cracks depending on the other variables, for the high severity cracks (wider than ¾ -inch), the crack width may be too wide for the router to reach both sides of the crack during the routing operation. Therefore, the clean-and-seal method is more appropriate for high severity cracks.

6.1.2 Pavement Type and Age

The type of the pavement, whether it is new construction or an overlay, play a role in the crack treatment schedule and the selection of the crack sealing method. The age of the pavement, depending on the sealing is intended for the initial years of the service or for towards the end, can influence the selection of the crack sealing method. Table 33 shows a couple of examples of MnDOT's crack treatment schedules for new constructions and overlays with varying design life and analysis period (MnDOT, 2018a). In Table 33, it can be seen that the new pavement with a 20-year design life, with a 35-year analysis period will receive crack treatments twice - at the 8-year and 23-year mark. Then pavement with a 50-year analysis period, will receive crack treatments thrice - at 8-, 23-, and 40-year mark. A pavement overlay with a 13-year design life and a 35-year analysis period receive crack treatments thrice - at 3-, 16-, and 28-year mark. A pavement overlay with an 18-year design life and a 35-year analysis period receive crack treatments twice - at 3- and 21-year mark. These different pavement ages or crack treatment numbers (e.g., first, second and third treatments), and the pavement type (new vs. overlay) influence the choice of the crack selection method.

Table 33. Crack Treatment Schedule (MnDOT 2018a)

(a) New HMA, Design life 20 years

	35 Year Analysis Period	50 Year Analysis Period
Pavement Age	Treatment	Treatment
0	Initial Construction	Initial Construction

8	*Crack Treatment*	*Crack Treatment*
12	Surface Treatment	Surface Treatment
20	Mill & Overlay (1st Overlay)	Mill & Overlay (1st Overlay)
23	*Crack Treatment*	*Crack Treatment*
27	Surface Treatment	Surface Treatment
35	End of Analysis Period	
37		Mill & Overlay (2nd Overlay)
40		*Crack Treatment*
44		Surface Treatment
50		End of Analysis Period

(b) Overlay, Design life 13-17 years

Pavement Age	**Treatment**
0	Initial Construction (1st Overlay)
3	*Crack Treatment*
7	Chip Seal
DL	Mill & Overlay (2nd Overlay)
DL+3	*Crack Treatment*
DL+7	Chip Seal
2*DL-1	Mill & Overlay (3rd Overlay)
2*DL+2	*Crack Treatment*
2*DL+6	Chip Seal
35	End of Analysis Period

(c) Overlay, Design life >17 years

Pavement Age	Treatment
0	Initial Construction (1st Overlay)
3	*Crack Treatment*
7	Chip Seal
DL	Mill & Overlay (2nd Overlay)
DL+3	*Crack Treatment*
DL+7	Chip Seal
35	End of Analysis Period

6.1.3 Traffic Level

Pavements are designed for different levels of traffic, from under a million to 30 million equivalent standard axle loads (ESALs). According to MnDOT standard specifications for construction (2018), the road with the traffic levels 2 (< 1 million ESALs) and 3 (1 to 3 million ESALs) are considered as the low volume roads; whereas, roads with traffic levels 4 (3 to 10 million ESALs) and 5 (10 to 30 million ESALs) are considered as the high volume roads. Even though a clear and convincing relationship between the service period of crack seals and traffic volumes could not be established in this project (because of the limitation of the data), it is believed that the traffic volume affects the life and performance of the crack seals. A high volume road needs a superior performing sealing method, such as rout-and-seal but also depends on other variables. It may be assumed that the higher the traffic, the greater the damage to crack seals. Hence, for the intermediate crack treatment, it is reasonable to consider clean-and-seal for traffic levels 2 and 3 and rout-and-seal for traffic levels 4 and 5.

6.1.4 Soil /Subgrade Type

The moisture-holding behavior and frictional resistance offered by the subgrade soil depends on its type (gravel, sand, silt, clay, etc.). The type of the soil, therefore, influences the seasonal movement of crack width as well. In this project, it was found that some practitioners expressed better performance of rout-and-seal for clayey and silty soils and clean-and-seal for sandy soils. Based on that observation, it is reasonable to choose rout-and-seal for clayey and silty soil conditions, whereas the clean-and-seal for sandy subgrade soils.

6.1.5 Cost factors

The initial crack treatment cost of the rout-and-seal method was found to be 1.8 times higher than the clean-and-seal method due to the specialized equipment and additional time required for routing. In today's dwindling budget scenario, the crack treatment cost can play a significant role as well. Hence, it is reasonable to consider the clean-and-seal method irrespective of other variables when a sufficient fund is not available.

6.1.6 Practitioners' Preference

The online survey conducted in this project revealed that many practitioners prefer the rout-and-seal for sealing cracks at initial years of the service period, and the clean-and-seal for later years; this practice is somewhat working as well. Keeping in view of this, it is reasonable to consider the rout-and-seal for the first crack treatment and clean-and-seal for the last crack treatment in the analysis period.

6.2 CRACK SEALING SELECTION CRITERIA

As discussed above, the selection of the crack sealing method could be influenced by several variables. Besides, these variables may not necessarily have an identical weightage. A decision worksheet was developed to account for the non-uniformity in the weightages of these variables.

Table 34 shows the list of decision variables and their respective weightages. The weightage (%) of the crack treatment cost, benefit/cost ratio, expected service life of the seal, ease of repair, practitioners' preference, and traffic level were decided as 10, 15, 15, 10, 30 and 20 percentages, respectively. Although the percent weightages of these decision variables are subjective, they were logically assumed based on the experience gained in this project and reviewing different literature related to crack sealing practices. As there was no significant difference found in the benefit/cost analysis, a relatively high weightage was assigned to the practitioners' opinion. Separate scores (%) were given to the two crack sealing methods. The scores for some of the variables mentioned above were determined based on the findings from the cost analysis performed in Section 5. For example, the crack treatment cost for rout-and-seal was 1.8 times more than the clean-and-seal; therefore, a score of 64 is assigned to the clean-and-seal, and a score of 36 was assigned to the rout-and-seal (64:36 = 1.8:1). A similar procedure was followed for the scores for the benefit/cost analysis as well. The typical service life of the rout-and-seal is generally four years versus three years for the clean-and-seal method; the scores for the expected service lives for these methods were thereby assigned based on this assumption. As there is no quantitative assessment available for the remaining three variables listed in

Table 34, qualitative scores were assigned to them. The scores for the practitioners' opinion and traffic level were varied for the crack treatment numbers and traffic levels.

The weighted scores for each decision variable were calculated by multiplying the score with the corresponding weight. The last two columns of

Table 34 provides the total scores for all the decision variables together and ranks for two crack sealing methods for various traffic levels and crack treatment number.

Table 34. Decision worksheet for crack sealing selection criteria

Decision Variables		Crack Treatment Cost	B/C Ratio*	Expected Life	Ease of Operation	Performance Opinion by Practitioners	Traffic Level	Total Score	Rank
Weight / Alternatives		10	15	15	10	30	20		
1st Treatment, All Traffic Levels									
Rout-and-Seal	Score	36	53	57	33.3	60	50	51.43	1
	Weighted Score	3.6	7.95	8.55	3.33	18	10		
Clean-and-Seal	Score	64	47	43	66.7	40	50	48.57	2
	Weighted Score	6.4	7.05	6.45	6.67	12	10		
Intermediate, Traffic Levels 2 and 3									
	Score	36	53	57	33.3	50	40	46.43	2

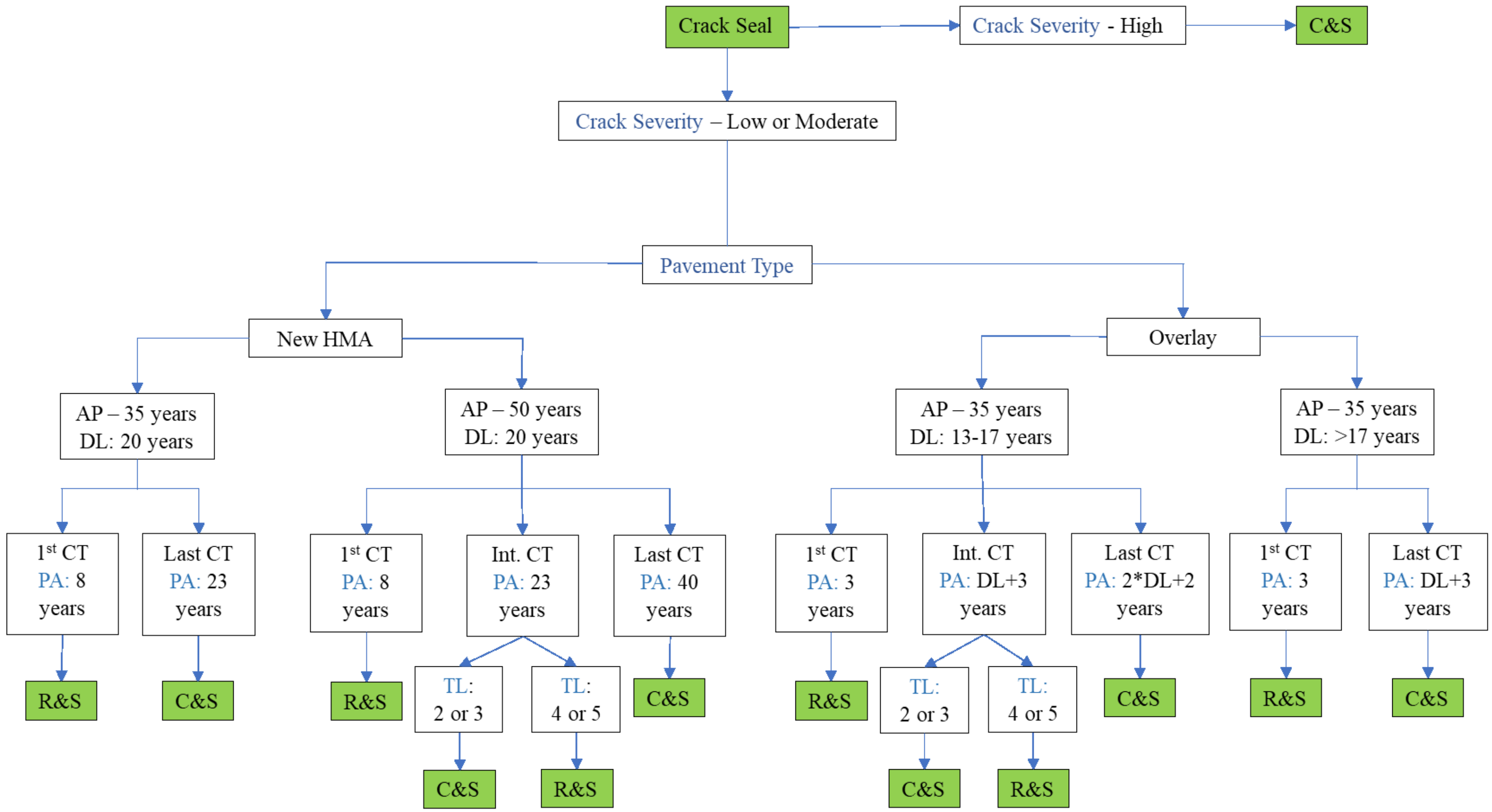
Rout-and-Seal	Weighted Score	3.6	7.95	8.55	3.33	15	8		
Clean-and-Seal	Score	64	47	43	66.7	50	60	53.57	1
	Weighted Score	6.4	7.05	6.45	6.67	15	12		
Intermediate, Traffic Levels 3 and 4									
Rout-and-Seal	Score	36	53	57	33.3	50	75	53.43	1
	Weighted Score	3.6	7.95	8.55	3.33	15	15		
Clean-and-Seal	Score	64	47	43	66.7	50	25	46.57	2
	Weighted Score	6.4	7.05	6.45	6.67	15	5		
Last Treatment, All Traffic Levels									
Rout-and-Seal	Score	36	53	57	33.3	40	50	45.43	2
	Weighted Score	3.6	7.95	8.55	3.33	12	10		
Clean-and-Seal	Score	64	47	43	67.7	60	50	54.67	1
	Weighted Score	6.4	7.05	6.45	6.77	18	10		

*B/C Ratio: (PI, %) / (LCC, 1000$ per lane-mile)

6.2.1 Decision Trees

The rankings determined in the previous section was helpful in developing two decision trees that can be used for the selection of the appropriate crack sealing method. The first decision tree is shown in Figure 6.1. Using this decision tree, users can decide on the most appropriate crack selection method in terms of the variables discussed in the previous sections. For example, for a low severity crack in a newly constructed pavement with a 20-year design life and a 35-year analysis period, the crack sealing method for first-time crack treatment would be the rout-and-seal. A clean-and-seal method would be appropriate for a pavement with a sandy soil subgrade, and a rout-and-seal would be appropriate for the pavement with clayey and silty soil subgrades, irrespective of other variables.

The second decision tree which is a simplified version of the first one is shown in Figure 6.2. This decision tree can be useful when data on the decision variables are limited. As shown in Figure 6.2, a crack sealing method can be decided based on the crack severity, traffic levels and crack treatment number (first, intermediate or last). If the crack severity was high, a clean-and-seal method could be chosen. For low or moderate crack severity, the choice depends on the number of crack treatment in the analysis period and traffic level. If it is a first crack treatment for any traffic levels or the second crack treatment with traffic levels 4 or 5, a rout-and-seal method is suggested. If it is the last crack treatment for any traffic levels or the second crack treatment with traffic levels 2 or 3, a clean-and-seal method is suggested.



Crack Severity = Low: CW<1/4", Medium:1/4"<CW≤3/4", High: CW>3/4"; CW= Crack Width
AP = Analysis Period; DL = Design Life; CT = Crack Treatment; PA = Pavement Age; TL = Traffic Level; R&S = Rout-and-seal; C&S = Clean-and-seal

Figure 6.1. Decision tree for selection of crack sealing method

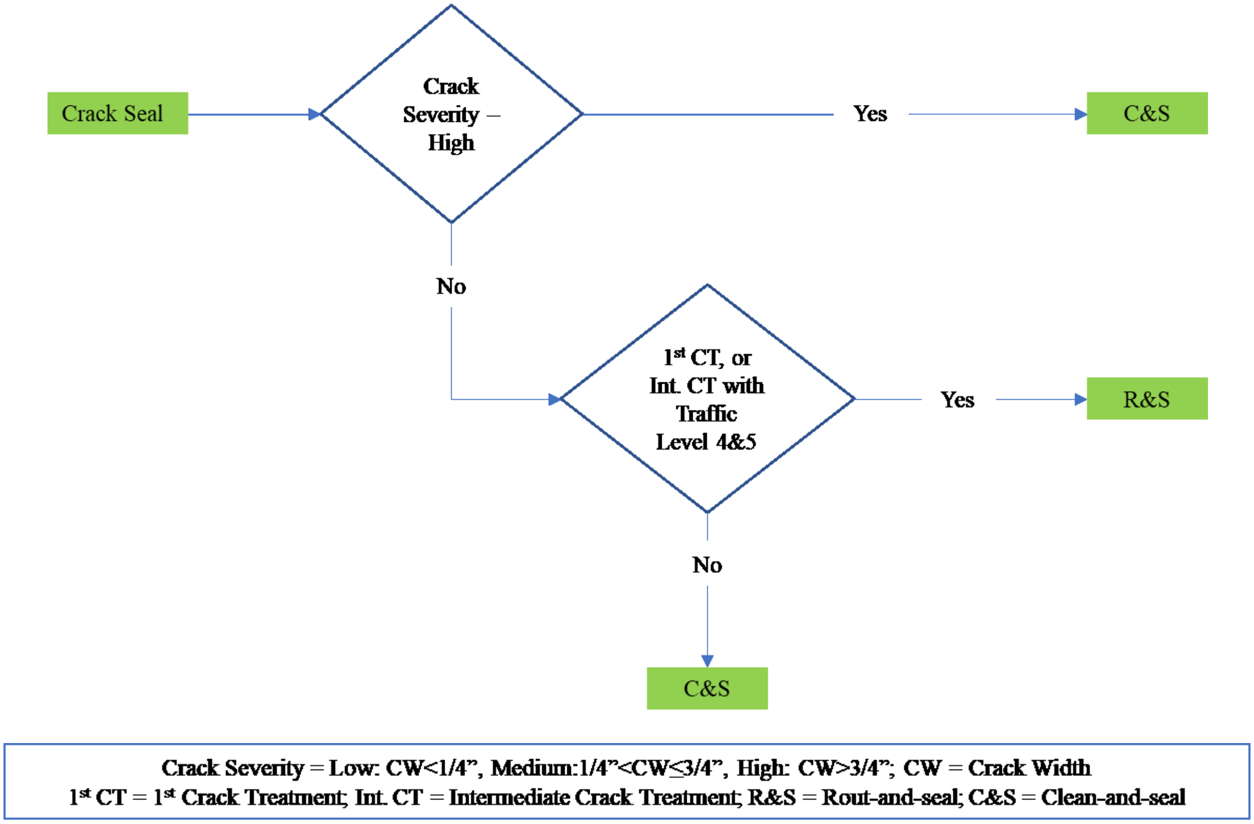


Figure 6.2. Simplified decision tree for selecting a crack sealing method

CHAPTER 7: SUMMARY AND CONCLUSIONS

Crack sealing is an important preventive treatment in a pavement preservation program. In order to achieve a cost-effective crack seal, it is important to select a proper crack sealing method. While the state of Minnesota usually seals cracks of asphalt pavements, there is no clear consensus on the most appropriate crack sealing method for a specific job. The main goal of this study was to develop a guideline so that an effective crack sealing method can be chosen based on the factors that influence the performance of crack seals, such as, traffic level, pavement age, crack severity, crack sealing occurrence number (e.g. sealing the pavement for the first time, 2nd time or 3rd time), etc. The following major tasks were performed in this project: (i) literature review on the crack sealant installation practices and sealant performances, (ii) collection and analysis of field performance data (iii) performance- and cost-effectiveness analysis, and (iv) development of a guideline.

Various literature on the crack sealant practices and performances, including research reports, synthesis, journal articles, and other relevant publications were reviewed. The crack sealing performance data was collected through an online survey and reviewing the history of crack sealing projects documented in several construction data logs of MnDOT. Performance data were also collected through periodical evaluations of crack seals at 35 different sites located throughout Minnesota. The performance of the crack seals was studied by quantifying the performance index of the crack seals. The effectiveness of the crack seals was studied with respect to the benefit-cost ratio analysis. Finally, two decision trees were developed to help to select the most appropriate crack sealing method, one of which can be used in the pavement management systems and the other can be used by the preventive maintenance crews. The major specific conclusions drawn from different tasks of this study are listed below:

<u>Online survey (Phase 1)</u>

- It was found that the rout-and-seal (of transverse thermal cracks) is the most commonly practiced crack sealing method in Minnesota. Out of the 47 responses received in the online survey, 68% revealed that they use rout-and-seal method and the other 32% use clean-and-seal method.
- A mixed response was received regarding the service life (time of sealant installation to failure) of rout-and-seal and clean-and-seal treatments. The opinions ranged from 2 to 10 years for clean-and-seal and 2 to over 15 years for rout-and-seal.
- The most commonly reported criterion for selecting a sealing method was crack/pavement conditions (41%) followed by pre-determined schedules (24%), no criteria (17%), pavement age (13%), subgrade material (2%), and budget (2%).

<u>MnDOT Construction log data (Phase 2)</u>

- The average service periods (time of sealant installation to next maintenance or rehabilitation work) of the rout-and-seal and clean-and-seal methods were found to be around 6.4 and 6.0 years, respectively. The difference in average service periods between the clean-and-seal and rout-and-seal was found to be statistically insignificant (at a 95% confidence level). However, it shall be mentioned here that the amount of clean-and-seal data was limited compared to the rout-and-seal data.
- Average service periods of 6.9 and 6.4 years were found for the roads with lower traffic (<10,000 AADT) and 5.4 and 5.3 years of average service periods were found for the roads with traffic higher

(>10,000 AADT) for rout-and-seal and clean-and-seal treatments, respectively. Though a higher service period was found with lower traffic, the difference between the average service periods of these two traffic categories was found to be statistically insignificant (at a 95% confidence), for both methods.

<u>New crack seal project sites (Phase 3)</u>

- After the first-year evaluation (one summer and winter), the average performance indices for the rout-and-seal and clean-and-seal projects were found to be 85 and 90, respectively. For the second winter evaluations, the average performance indices for both seal methods were found to have dropped significantly, seals deteriorated quicker than it was anticipated. The reason for this unanticipated drop of the performance index is probably the severely cold 2018-2019 winter, which expanded many cracks beyond the typical average winter crack widths and stretched sealants beyond their allowable strains.
- A large amount of spalling failure was observed in rout-and-seal sections. Although not formally addressed as a seal failure for calculating performance in other studies, spalling was found to be contributing to a large portion of performance loss in the cracks documented for this study.
- Sites documented with rout-and-seal also experienced a large number of adhesion failures. This failure was seen more commonly with increased crack spacing.
- The short-term performance for closely spaced cracks on a rural road is identical for both clean-and-seal and rout-and-seal.
- Cohesion failure has not yet been observed in this study.

<u>Old crack seal project sites (Phase 4)</u>

- Only rout-and-seal project data was available for the old crack seal sites. Although the PI drop for these sites during the second winter was not as large as the new crack project sites, the drop was noticeable.

<u>Effectiveness of the crack sealing methods</u>

- Data from the new and old crack seal sites were used to develop the relationship between the average performance index and age of the seals; a reasonable correlation was found with an R^2 = 0.95.
- The performance data of crack seals were used to study the effectiveness of the crack sealing method. A threshold PI value of 50 was assumed to determine the service lives of the crack seals. It was found that the rout-and-seal and clean-and-seal methods have approximately 4 and 3-year service lives, respectively. The decision on these service lives was made based on the data collected in this project as well as relevant crack seal performance data found in several literature.
- The life-cycle cost analysis (LCCA) and benefit-cost ratio analysis showed that the rout-and-seal was more effective than clean-and-seal due to its longer performance period. However, if only a short-term benefit is considered, then the clean-and-seal could be more cost-effective than its counterpart.
- As the benefit/cost analysis did not yield a clear distinction between the effectiveness of the two crack sealing methods, several other decision factors were then considered to determine the

effectiveness of each crack seal method. Various factors such as treatment cost, B/C ratio, expected life, ease of operation, practitioners' opinion, and traffic level were considered.

- Two decision trees were developed for choosing the most appropriate crack sealing method. The first one, which can be used for a pavement management system, needs more information such as crack severity, pavement type (new vs. overlay), pavement analysis period and design life, traffic level, and crack seal occurrence number. The second decision tree, which is a simplified version of the first one and can be used by the preventive maintenance crews, needs less information such as, crack severity, traffic level, and crack sealing occurrence number. In general, the clean-and-seal method was found to be appropriate for high crack severity conditions. The choice between rout-and-seal and clean-and-seal for low and moderate crack severity was found to be varied based on pavement type and age, and traffic levels. The clean-and-seal method was found to be appropriate for sandy soil subgrade and the low initial budget scenario, whereas the rout-and-seal method was preferred for clayey and silty subgrades irrespective of other variables.

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