District Highway Maintenance Research On-Call (ROC) 2023-09-Task 1: Evaluation of the Use Robotic Systems for Improving Crack Sealing Process

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16. Abstract

This report summarizes the results of a research task that was conducted to document the Ohio Department of Transportation (ODOT) current state-of-the-practice for crack sealing, identify best practices used or researched by state DOTs for crack sealing, and identify new methods and equipment for crack sealing that can improve the efficiency, response time, and safety of maintenance crews. To achieve these goals, a comprehensive literature review of all studies on the best practices for improving the efficiency and safety of crack sealing installation was conducted. In addition, surveys were performed to gather information from DOTs and local public agencies. Robotic Maintenance Vehicle (RMV) was identified as an equipment that might help improve the efficiency of crack sealing operation and workers safety. However, currently there is not enough information or experience with using this equipment to validate its capabilities or benefits. The results of cost analysis conducted in this study indicated that RMV may result in reducing the cost of crack sealing for ODOT. However, the RMV cost savings depend on several assumptions made that could not be validated at the current time. Therefore, all assumptions made need to be verified before making final conclusions on the RMV cost effectiveness and its benefits to ODOT.

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District Highway Maintenance Research On-Call (ROC) 2023-09- Task 1: Evaluation of New Methods for Improving Crack Sealing Process

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1. Project Background

As pavement deteriorates different types of cracks occur. Crack sealing is a pavement preservation technique used to fill the cracks to reduce moisture infiltration and prevent the potential for accelerated deterioration. Crack sealing is expected to improve pavement performance and extend pavement life if performed in a timely and effective manner (*1*). Although crack sealing is one of the common tasks that maintenance crews at ODOT county garages frequently conduct, it can often be challenging as it is weather-dependent, slow-paced, and labor intensive. In addition, frequent breakdowns of equipment can cause significant downtimes. Crack sealing maintenance crews are also exposed to many hazards including traffic and hot asphalt sealing materials. These challenges can lead to delayed response times in crack sealing, which negatively impacts the pavement and can adversely affect the safety of the workforce and traveling public.

Fortunately, emerging technological breakthroughs in robotics show promise for improving the efficiency and safety of the crack sealing process. To this end, autonomous robotic crack sealing systems have been proposed and developed, and at least one system is commercially available at the current time. These systems can take crack data from an external sensor, extract connected crack paths, and link those paths to plot the motion a robotic system can follow to seal the crack (*2*). Real-world testing has shown that robotic crack sealing systems can successfully be used to fill pavement cracks (*3*). Although autonomous robotic crack sealing systems have tremendous potential to enhance the efficiency, safety, and quality of pavement crack sealing, no study has evaluated the reliability and cost-effectiveness of such systems.

This Research-On-Call Task will document the best practices for crack sealing process. It will also identify cost-effective and reliable new equipment and technologies that can help improve the efficiency and safety of ODOT's crack sealing process and reduce the response time of ODOT county garages to perform crack sealing.

2. Research Context

The objectives of this task are:

- Document the current state-of-the-practice for crack sealing.
- Summarize the results of different studies on crack sealing.
- Prepare a synthesis of best practices used or researched by other state DOTs related to the problem statement.
- Identify new methods and equipment for crack sealing that can improve the efficiency, response time, and safety of maintenance crews.
- Provide recommendations for the next steps that need to be taken by ODOT to improve the current crack sealing process.

3. Research Approach

3.1 Perform Literature Review

This task involved conducting a comprehensive literature review of all active and completed studies on crack sealing process. The research team reviewed the existing literature to identify the crack sealing methods, equipment, and materials that can help in improving the efficiency and safety during the crack sealing installation process as well as enhancing the performance and effectiveness of the installed crack sealant. Special focus was on studies that used new and emerging technologies to reduce the time workers spent in the field during crack sealing installation and reduce the risks of exposure to hot liquid asphalt binder.

The literature search included all standard databases such as Transportation Research Information Services (TRIS), National Transportation Information Service (NTIS), Compendex/Engineering Village, and Web of Science. In addition, the research team consulted with national and international experts on this subject. Appendix A provides a summary of all studies reviewed and present synthesis of best practices for crack sealing installation used or researched by other state DOTs.

3.2 Identify ODOT Current Practices for Crack Sealing

The research team assessed the current ODOT state-of-the-practice for crack sealing. To achieve that, a survey was conducted to gather information and seek details from ODOT county garages about different approaches and devices/systems (if any) used for crack sealing. The research team ensured that the survey included clear, concise, and well-targeted questions. Appendix B provides details about the survey. In addition, the results of the conducted survey are presented in Appendix C. The research also visited Districts 1 to document their current practices for crack sealing and discuss any issues pertaining to installation of crack sealing.

3.3 Identify Best Practices for Crack Sealing Installation

The research team conducted a comprehensive online survey to gather information from DOTs and local public agencies and to fill gaps in the results of the literature review. The research team ensured that the survey included clear, concise, and well-targeted questions. The survey sought information about the cost-effective and innovative crack sealing methods/practices and materials that had been successfully used by these agencies, which resulted in enhancing the productivity, efficiency and safety of crack sealing process and improved performance and longevity of installed sealant. In addition, the survey identified practices used to reduce the risks of hot asphalt binder during crack sealing installation. The survey also collected the following information about the cost-effective and innovative crack sealing methods/practices used: initial and operational costs, productivity (sealing time and number of persons needed), cost of equipment needed, user experience, limitation, and special materials needed. A draft survey questionnaire was sent to the TAC members for review before its distribution for solicitation of responses. The survey was updated based on the obtained comments and a direct link of the online survey was distributed via email. Appendix B provides details about the national survey. In addition, the results of the conducted national survey are presented in Appendix C.

3.4 Robotic Maintenance Vehicle (RMV)

The research team identified a new equipment called Robotic Maintenance Vehicle (RMV) that can be used to improve the efficiency of crack sealing process. RMV is a semi-autonomous system designed to assist in the pavement crack sealing process. It is the only commercially available system capable of sealing both longitudinal and transverse cracks. RMVs can also be used for sealing cracks in various pavement types, including asphalt, concrete, and composite pavements. The system consists of a truck-mounted Fanuc six-axis R2000 robotic arm, a SealMaster CrackPro 260 sealing unit, and an air blow-off system to remove road debris. The RMV is equipped with a high-resolution automated computer vision system to locate and measure cracks. The RMV crack sealer operates continuously at 2-5 mph and only requires a single operator to drive. The system's crack blowout and sealing process is fully autonomous, allowing for consistent and efficient crack sealing. Therefore, the RMV system reduces worker hazard exposure while increasing the speed and quality of pavement crack sealing, and ultimately saving money through lower labor requirements. Figures 1 and 2 show pictures of the RMV.

Figure 1: Robotic Maintenance Vehicle (RMV).

The RMV incorporates advanced Artificial Intelligence (AI) software with three cameras and lasers mounted underneath the truck to scan the roadway while moving. It is crucial for the cameras to be hidden in the dark, as shown in Figure 3, so that the cameras work in all lighting conditions without the need for recalibration. The special lasers are equipped with different colors based on depth. A vision system by Vista solutions is used to recreate the entire area of the road surface.

Once the AI models analyze the image, they determine the locations of the cracks. While the truck is moving, the road profile generated by the AI model is transformed into the robotic arm frame of reference, and the Seal Master pumps the crack sealer along the crack path. If the robotic arm is unable to keep up in sealing with the speed of the vehicle, a red light is switched on as a warning to the driver to stop until the sealing is finished, which then reverts back to green. The sealing covers a full lane width, and the vehicle is equipped with lights to warn drivers to turn away from the RMV.

Figure 2: RMV Prototype Vehicle

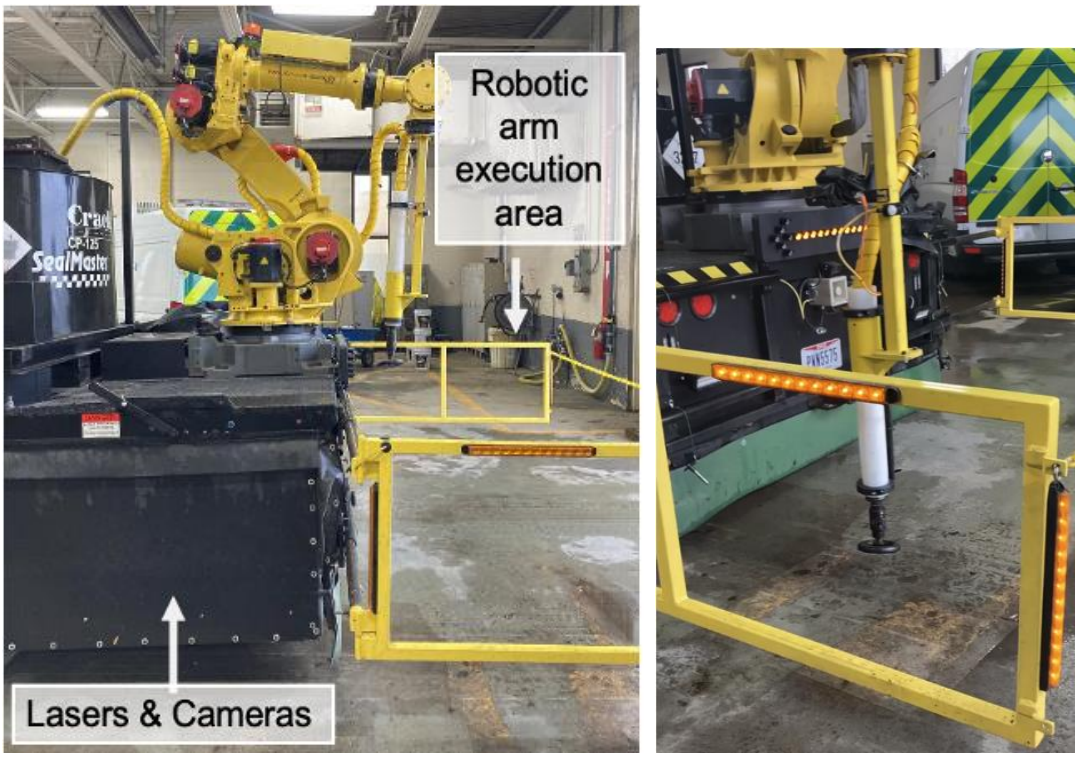

Figure 3: RMV robotic arm execution area, cameras', and lasers' location.

According to manufacturer, the RMV has been tested by several organizations, including the New Mexico Department of Transportation, Indiana Toll Road Authority, and the United States Air Force. These organizations have shown some interest in adopting the system due to its potential to increase the speed and quality of pavement crack sealing while improving safety and saving money through lower labor requirements and worker hazard exposure.

A demonstration was provided by the RMV manufacturer to the Ohio Department of Transportation on November 1st, 2022. In this demonstration it was noted that several improvements to the final production model of the RMV would be made to improve performance: (1) all production RMV systems will be built upon a new F-550 (or equivalent) chassis, (2) the blower motor and diffuser bar will both be upgraded in production to allow for easier height/angle adjustment while using 15 CFM versus the 10 CFM, (3) range of motion for the robotic arm will be 12ft for the production model, and (4) crack sealant application efficiency (quantity and penetration) was improving steadily as they receive data from continued testing and demonstrations for algorithm training. The demonstration suggested that the system has some potential to increase the speed and quality of pavement crack sealing while improving safety and saving money.

3.5 Cost Analysis

The research team conducted a cost-benefit analysis to evaluate the cost-effectiveness of using the RMV for crack sealing and compare the cost of the RMV process to current ODOT practices for crack sealing. The data was obtained from ODOT Districts 1 and 2 for all crack sealing work done in-house and contracted out. For work done in-house, cost information was obtained for each county and based on work orders. Less information was available for the crack sealing work contracted out. Therefore, the cost analysis focused on in-house crack sealing.

3.5.1 ODOT Current Crack Sealing Cost

Figures 4 and 5 present the material, equipment, and labor costs as well as the total cost of in-house crack sealing conducted at the different counties in Ohio Districts 1 and 2 during past years (2021 and 2022). Most of the counties had a higher cost for crack sealing in 2021 as compared to 2022. For instance, the total labor cost in Putnam County decreased from $250,000 in 2021 to below $20,000 in 2022. This observation can be attributed to two reasons. First, the cost information was obtained in November 2022, so the cost does not cover the entire crack sealing done in 2022. Second, the 2022 cost have included fewer crack sealing activates due to rehabilitation projects done on state routes in 2021.

3.5.2 Robotic Maintenance Vehicle Cost Saving

A meeting was held with Robotic Maintenance Vehicle (RMV) company to obtain the cost and benefits of the RMV vehicle. The company currently offers purchase and lease options. In terms of purchasing equipment, the RMV price is $1,050,000 for a purchase, which excludes any special option selected. The company is offering a discount on the purchase price of $979,000 for the next 12 trucks that are sold. If a customer decides to supply the chassis, the purchase price would be reduced by $85,000. The company includes a one-year warranty on purchased equipment, which covers parts and labor for the entire system except the truck itself. An extended warranty option is available for up to 7 years.

On the other hand, the lease option includes paying $50,000 down payment and a fee that depends on the linear foot of cracks sealed. As shown in Table 1, the fee rate for the first year is $0.055 per linear foot and increases by $0.001 each subsequent year until it reaches $0.061 per linear foot in the seventh year. On average, the RMV company indicated that there is approximately 20,000 linear feet of crack sealing per mile, resulting in an average cost of $1,170 per mile. The lease option requires a minimum commitment of 7 years, with a minimum annual fee that starts at $150,000 in the first year and increases to $180,000 in the seventh year. The lease option covers all equipment maintenance and includes access to all crack sealing data.

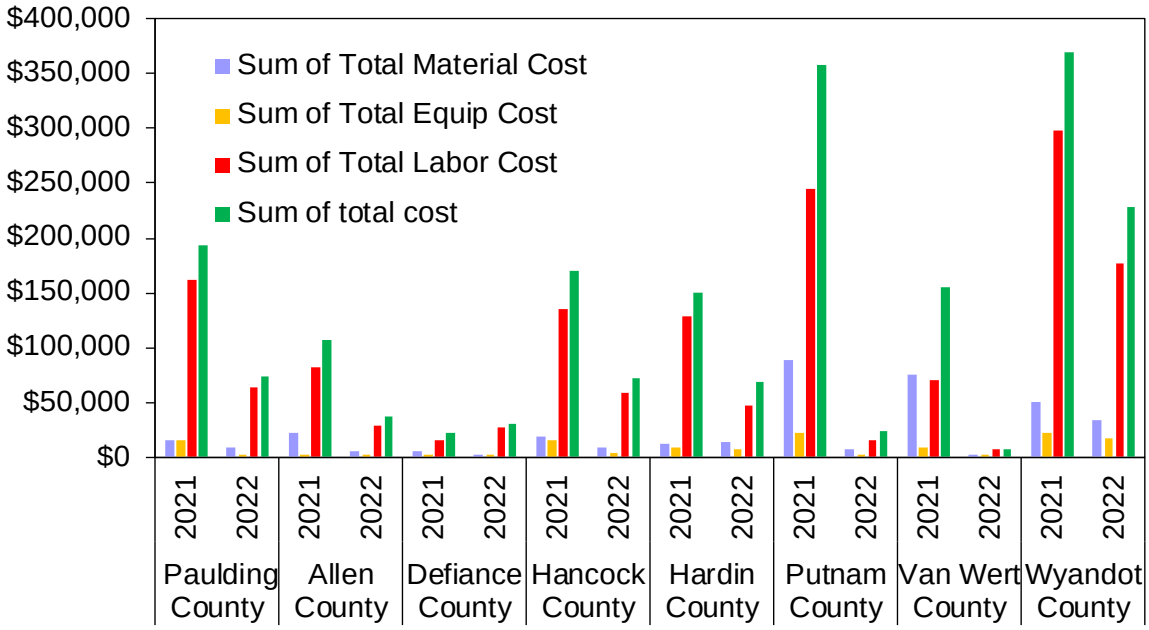

Figure 4: Crack sealing material, equipment, and labor cost during 2021 and 2022, District 1.

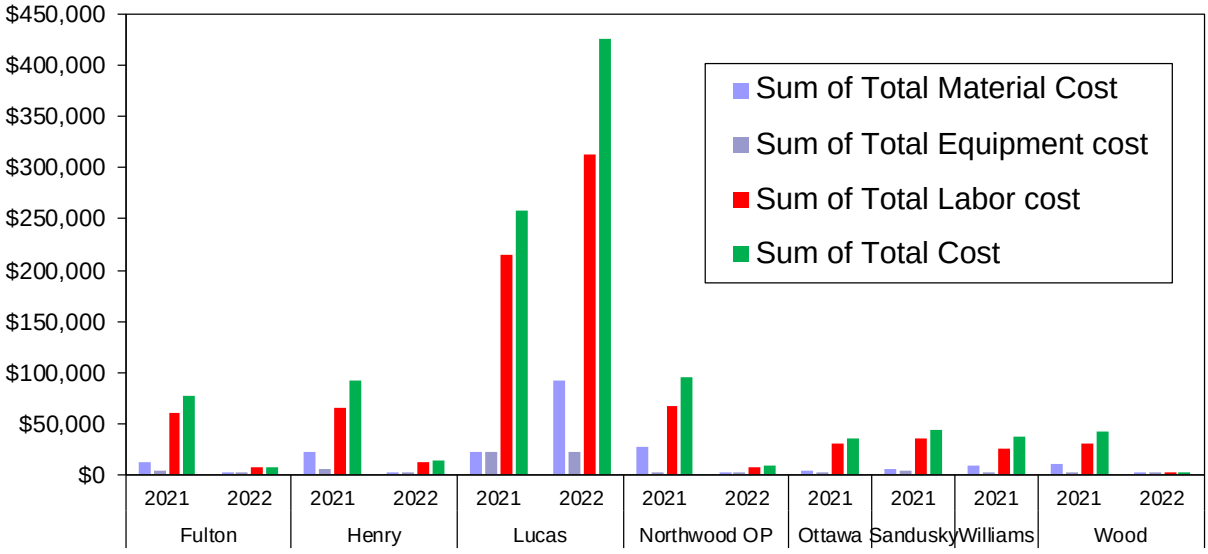

Figure 5: Crack sealing material, equipment, and labor cost during 2021 and 2022, District 2.

Table 1: Lease Option Rates and Minimum Fees for Crack Sealing.

Year	1	2	3	4	5	6	7
PLFCS Rate	$0.055	$0.056	$0.057	$0.058	$0.059	$0.060	$0.061
Minimum Annual Charge	$150,000	$155,000	$160,000	$165,000	$170,000	$175,000	$180,000

Based on the discussion that was held with Putnam County, it has been estimated that an average of one pallet (2250 lb) is used for every two miles of cracked road section during crack sealing. To estimate the cost of the RMV, data provided by District 1 and District 2 was utilized. Using this data, the cost of RMV was estimated based on its accomplishment, with the added benefit of being able to seal cracks along the center line as well as within the lane simultaneously.

When crack sealing is done using the RMV, only two flaggers, a driver and another worker will be required, which results in reducing the labor costs. Additionally, all RMV maintenance will be covered through the lease contract. Based on that, it was estimated that the use of RMV will result in a 50% reduction in labor costs and a 50-60% reduction in equipment costs. Table 2 and 3 show the current ODOT cost of crack sealing and the estimated cost using RMV for both District 1 and District 2, respectively.

Table 2: District 1 Cost Analysis Results

Year	Current ODOT Cost	RMV Cost	Cost With RMV	Saving
2021	$927,460.89	$196,865.89	$739,037.59	$188,423.30
2022	$469,080.87	$98,097.09	$295,305.21	$173,775.66
Total	$1,396,541.76	$287,808.69	$1,027,188.51	$369,353.25

Table 3: District 2 Cost Analysis Results

Year	Current ODOT Cost	RMV Cost	Total Cost with RMV	Saving
2021	$664,807.03	$168,391.75	$551,769.34	$113,037.69
2022	$504,009.06	$78,936.13	$367,773.11	$136,235.95
Total	$1,168,816.09	$240,173.59	$912,388.15	$256,427.94

Table 2 shows the cost analysis of utilizing Robotic Maintenance Vehicle (RMV) for crack sealing projects compared to the current Ohio Department of Transportation (ODOT) cost estimates. The table displays data for the years 2021 and 2022, as well as the total estimated cost savings. For the year 2021, the current ODOT cost for crack sealing is $927,460.89, while the RMV cost is $196,865.89, resulting in a cost of $739,037.59 when utilizing RMV. This yields a savings of $188,423.30 when compared to the current ODOT cost. Similarly, for the year 2022, the ODOT cost saving would $173,775.66 if RMV was used. Overall, the total cost savings of using RMV for the two-year period is $369,353.25. These findings demonstrate the potential benefits of adopting RMV in future crack sealing projects, resulting in substantial cost savings for the ODOT. However, the estimated savings assumes that ODOT will use the RMV enough to meet the minimum required annual fee.

Table 3 shows the cost savings of using RMV for District 2 over 2021 and 2022. The RMV cost is significantly lower than the current ODOT cost, resulting in total cost savings of $256,427.94. In 2021, the RMV cost was $168,391.75, resulting in a savings of $113,037.69 compared to current ODOT cost for crack sealing activities. In 2022, the RMV cost was $78,936.13, resulting in a savings of $136,235.95. These results of table 2 and 3 demonstrate that using RMV for crack sealing maintenance can be a cost-effective solution for both District 1 and 2.

3.5.3 Effect of Robotic Maintenance Vehicle Minimum Annual Fee on Cost Saving

The minimum annual cost specified in the lease option requires ODOT to perform crack sealing for certain number of miles. To ensure this is met, the speed of the RMV and assumptions provided by the manufacturer were considered. Analysis was conducted to determine the specific number of miles and days of crack sealing required to achieve this minimum cost. The analysis involved first examining several cases to determine the impact of the minimum specified annual cost on the savings. Table 4 presents the different cases that were considered, and assumptions made in each case. As shown in the Table 4, the cost of per mile of cracked road in all cases is the same, which is computed based on the average seven-year RMV cost rate per linear foot of crack of $0.0585, and an estimate of 20,000 linear feet of crack per mile, which was provided by the RMV manufacturer. In addition, based on an average seven-year minimum annual fee of $165,000 required in the lease option and the computed cost of per mile of cracked road, 141 miles of cracked road sections is required to be sealed by ODOT every year. The different cases provide the number of days ODOT needs to perform crack sealing on 141 miles of cracked road sections, assuming different RMV speed and hours of crack sealing per working day. While an RMV speed of 0.25 mph was assumed for cases 1 and 2, a speed of 0.5 mph was assumed for case 3 and 4. In addition, The hours of crack sealing per working day varied between 4 to 5, which was based on information provided by ODOT districts. Table 4 shows the number of days per year required by ODOT to perform the necessary crack sealing on 141 miles of cracked road sections. It is noted that the number of days varies between 141 for Case 2 to 57 for Case 3.

Table 4: Cases Evaluated for Cost Analysis

Parameter	Case 1	Case 2	Case 3	Case 4
Rate per linear ft of crack	$0.0585	$0.0585	$0.0585	$0.0585
Linear foot of crack per mile	20000	20000	20000	20000
Rate per mile of cracked road	$1,170	$1,170	$1,170	$1,170
Minimum fee per year	$165,000	$165,000	$165,000	$165,000
Miles needed to be crack sealed each year	141	141	141	141
Hours of crack sealing per working day	5	4	5	4
RMV Speed (mph)	0.25	0.25	0.5	0.5
Days of crack sealing each year	113	141	57	71

Analysis was then conducted to account for the minimum annual fee specified in the lease option on the computed cost savings in Table 2 and 3 for the different cases considered in Table 4. Tables 5 and 6 show the results of analysis for the four different cases when they are applied in District 1 and District 2, respectively. The results in Table 5 indicate that Case 3 had the lowest extra cost for District 1 of $18,750 due to the minimum annual fee specified in the RMV lease

option. This results in the highest net savings of $155,026. In addition, Case 1 had the highest extra cost of $91,875, resulting in the lowest net savings of $81,901. Overall, all four cases resulted in extra cost due to the minimum annual cost specified in the RMV lease option, which lowered RMV cost savings for District 01.

Table 6 shows the results of the analysis for all four cases in District 2. In Case 1, the extra cost is $91,875.00, while the saving for District 2 is $113,038, resulting in a net saving of $21,163. Case 2 has the highest extra cost of $106,500.00, with a saving of $113,038, resulting in a net saving of $6,538. In Case 3, the extra cost is the lowest at $18,750.00, with a high saving of $113,038, resulting in the highest net saving of $94,288. Case 4 has an extra cost of $48,000.00 resulting in a net saving of $65,038. Overall, Case 3 has the highest net saving for District 2 due to its low extra cost and high savings.

Table 5: Cost Savings for District 01 Considering RMV minimum annual fee

Case	**Extra Cost**	**Saving for D1**	**Net Saving**
Case 1	$91,875.00	$173,776	$81,901
Case 2	$106,500.00	$173,776	$67,276
Case 3	$18,750.00	$173,776	$155,026
Case 4	$48,000.00	$173,776	$125,776

Table 6: Cost Analysis – RMV Cost, District 02

Case	**Extra Cost**	**Saving for D2**	**Net Saving**
Case 1	$91,875.00	$113,038	$21,163
Case 2	$106,500.00	$113,038	$6,538
Case 3	$18,750.00	$113,038	$94,288
Case 4	$48,000.00	$113,038	$65,038

3.5.4 Assumptions Made in Cost Analysis

It is noted that the cost analysis done in this project had some assumptions that could not be verified:

- There is average 20,000 linear foot of cracks per mile of road being repaired using RMV.
- No downtime of equipment.
- The RMV will detect all cracks and will properly seal them.
- Amount of crack sealant material used by the RMV is similar to that used by traditional manual crack sealing methods.
- The performance of crack sealed installed using the RMV is similar to those installed using traditional manual crack sealing methods.

In addition, the cost analysis did not consider RMV benefits that are harder to quantify including improving the safety of worker performing the crack sealing.

3.6 Experiences and Impression of Other Agencies

RMV provided a field demonstration to the staff of the New Mexico Department of Transportation (NMDOT) during the week of 3-7 October 2022. Dr. Hao Yin, the Director of NMDOT's Research Bureau at NMDOT, was interviewed on 13 October 2022 to provide his initial impressions about RMV. Overall, Dr. Yin feels that the RMV has strong potential to be a viable solution for large scale crack sealing applications in New Mexico (NM) but there are issues that should be addressed. During the field demonstration, operation of the system was abrupt because there was not any automated vehicle control or meaningful feedback for the driver. This lack of control and feedback meant the driver had to work constantly to ensure the vehicle was moving at the appropriate speed to match the robotic arm's rate of crack sealing. The result of this abrupt operation meant that bitumen application was inconsistent at times. Dr. Yin received feedback from several of his field technicians that the truck on which the RMV was mounted was a low-end model and system performance could be improved with a better truck. It should be noted that the truck currently being used for demonstrations of the RMV is an older model; purchased or leased RMVs will include a new truck platform for the system. Dr. Yin believes there is high potential for autonomous or semi-autonomous driver assist technologies to improve this aspect of system.

During a road test of several hundred yards on interstate highway 25 (I-25) in Albuquerque, NM, it was observed that RMV did miss approximately 30% of the cracks needing sealant. In Dr. Yin's opinion, the real-time crack identification algorithm still needs refinement to fully capture crack locations in real-time. Additionally, the algorithm struggles to differentiate deformations in the pavement's surface (e.g., rutting). This sometimes led to issues with the nozzle height not adjusting properly relative to the pavement surface which resulted in poorly applied sealant. The inability to adjust to pavement surface changes raised questions about how accurately the system can diagnose crack depth and apply the proper amount of bitumen as a result. Non-destructive quality checks of the sealing were not possible since personnel could not access the cracks during active sealing. RMV did tell Dr. Yin that they are relying on customers to build the training image datasets to feed their algorithm and improve performance over time. Dr. Yin remarked that the machine had much better performance sealing longitudinal cracks compared with transverse cracks.

In addition to inconsistent seal coverage, the RMV's robotic arm only has 8 feet of reach. As such, the 12-foot-wide lanes on I-25 needed two passes to fully cover one lane and requires a two-lane closure. The system also uses a rotating central blower to direct forced air at cracks. The performance of this method is marginal because forced air is not applied directly over each crack as with conventional manual application. A revised system that provides forced air more directly to each crack is needed to remove dirt and debris from cracks before applying sealant. During the demonstration of the RMV to ODOT, the RMV design team stated that an improved blower system (more adjustable with higher blowing power) and wider reaching arm would be standard on the production version of the system.

In terms of cost, NM is not ready to purchase a system outright. At a price of $1.1 million, NMDOT feels that the system needs more improvement to be worth the cost. However, a leasing option is available with a cost based on linear foot (LF) of cracks sealed. The seven-year lease terms consist of an initial $50,000 down payment and a cost structure of $0.050 - $0.065 per LF of sealing with minimum usage of 3,000 miles (about 4828.03 km) of cracks sealed per year. NMDOT is interested in using the RMV on a leased basis as early as the winter/spring of 2022/23.. NMDOT's current crack sealing crews consist of 5-8 personnel and can seal approximately 1.5

miles of roadway per day. Dr Yin thinks that the RMV has the potential to perform 2-3 times that amount with a crew of two people once the performance issues were ironed out.

On 2 December 2022, Mr. Preston Benedyk, Vehicle Control Program Manager for the Air Force Civil Engineer, provided his impressions of the RMV demonstration conducted at Tyndall Air Force Base, Florida. Mr. Benedyk highlighted two main concerns with the RMV system: (1) the RMV applied too much sealant material and (2) crack cleaning was insufficient for proper sealant adhesion. According to Mr. Benedyk, the RMV only missed 5-10% of the cracks it encountered but even the smallest hairline cracks were treated with large amounts of sealant. It was also observed that the applicator tracked sealant material between cracks, applying material where no cracks were present. This was not observed by NMDOT, and it could be because the USAF demonstration was conducted on airfield pavement with less dense cracking. It should be noted that the RMV system does include the ability for operators to input a manual correction factor for sealant quantity based on field observations.

For cracks with severe clogging or vegetation growth, the RMV is unable to clean these cracks. Mr. Benedyk did say that the USAF saw value in the machine despite this drawback. Typical airfield crack sealing operations require pre-seal routing and a machine like the RMV would allow two routing crews to operate with the RMV as opposed to the traditional single routing crew followed by a single sealing crew.

4. Research Findings and Conclusions

Appendices A, B, and C, present a detailed summary of the results and analysis of the literature review, surveys, interviews performed as part of this task. The main findings of this task are summarized below.

- The results of literature review indicated that crack sealing is cost effective when applied to pavements with PCR between 66 and 80.
- The results of literature review and the national survey indicated that crack preparation (cleaning and drying) is the most important step to ensure good performance of the installed crack sealant.
- The results of literature review indicated that the hot air lance effectively cleans and dries the wet cracks and provides better bonding between the materials and the surface of asphalt pavement than the conventional air compressors.
- The results of literature review indicated that routing is the most time-consuming method of crack preparation. Studies suggested it can double the service life and crack seals compared cleaning via compressed air. However, routing may be detrimental to pavements over 6 years old due to the aging of the mixture.
- The results of the ODOT survey indicated that some ODOT counties used crack sealing in the past but are no longer using it, mainly due to shortages in staffing.
- Almost all ODOT counties that perform cracking sealing reported being satisfied with the overall quality of installation.
- Equipment failure was reported as one of the major issues encountered by ODOT during cracking sealing. Therefore, in recent years, many ODOT counties resorted to renting crack sealing equipment instead of owning their own equipment.

- Results of analysis conducted on information provided by ODOT, indicated that the maintenance cost of the crack sealing equipment can be very high due to repetitive repairs of this equipment.
- The results of the national survey indicated that a fiber reinforced material with polymer and a smaller quantity of rubber has proven to be the best fit for states in the Northeast.
- Robotic Maintenance Vehicle (RMV) was identified as an equipment that might help improve the efficiency of crack sealing operation and workers safety. However, currently there is not enough information or experience with using this equipment to validate its capabilities or benefits.
- Feedback obtained through the national survey as well as interviews with selected agencies indicated that the RMV needs further development to be deemed a good option.
- The results of the cost analysis conducted in this study indicated that RMV may result in reducing the cost of crack sealing for ODOT. However, the estimated RMV cost savings depended on several assumptions made that could not be validated at the current time. Therefore, all assumptions made need to be verified before making final conclusions on the RMV cost effectiveness and its benefits to ODOT.

5. Recommendations

Based on the results of the of this study, the following recommendation are made:

- It is recommended to consider renting the equipment for crack sealing rather than buying it due to the high repair cost and downtime for this equipment.
- It is recommended to evaluate the use of hot air lance rather than conventional air compressors particularly when crack sealing is performed at colder temperatures.
- More data is needed to make final conclusions about the cost effectiveness of the RMV. It is recommended to obtain/verify the following information through a pilot study:
    - Average RMV productivity (miles that can be sealed in a day)
    - RMV downtime
    - RMV ability to accurately detect all cracks in roadways and properly seal them
    - Amount of crack sealant material used by RMV as compared to traditional manual crack sealing methods.
    - Performance of crack sealed installed using RMV compared to those installed using traditional manual crack sealing methods.

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Appendix A

Literature Review

A.1 Introduction

Cracking is an inevitable problem in asphalt concrete pavement and plays a significant role in pavement deterioration. A crack occurs when stress is built up in a pavement layer that exceeds the tensile or shear strength of the pavement materials. Therefore, when cracks develop on the surface of the pavement, they indicate a reduction in pavement integrity and serviceability [1]. To delay pavement deterioration, extend service life and maximize public funds, there is no better way than doing pavement maintenance [1]. Crack sealing and filling are pavement preservation techniques applied to in-service hot mix asphalt (HMA) pavements to reduce moisture infiltration to prevent the potential for accelerated deterioration. If performed in a timely and effective manner, crack sealing is expected to improve pavement performance and extend pavement life [2]. Crack sealing can be defined as the placement of specialized treatment materials above or into working cracks to prevent the intrusion of water and incompressible material into the crack. Crack filling is the placement of ordinary treatment materials into non-working cracks to reduce water infiltration and reinforce the adjacent pavement [3]. Working cracks are considered cracks that are more than 1⁄8″ in the summer and significantly larger in the winter [4]. Because crack sealing and filling work by closing the gaps present in pavement to block water infiltration, getting the appropriate fill material to as much of the crack as possible is key. National Cooperative Highway Research Program (NCHRP) Report 784 [4] provides many factors that affect the quality of asphalt crack maintenance:

- Evaluation of pavement condition and crack type (working or non-working).
- Crack preparation/routing prior sealing.
- Current and consistent crew training.
- Quality control testing for sealant products.
- Inspection of the crack treatment operations.
- Evaluation of sealant cohesion and adhesion performance over time.

Crack routing is used to widen cracks to accommodate enough sealant to provide an effective seal, even after the pavement crack opens due to contraction at low temperature during the winter months [5]. Adhesion is the binding force exerted by molecules of unlike substances when brought into contact and cohesion is the force by which molecules are held together so that the substance or body resists separation [6]. It is important that crack sealing is performed properly to avoid pavement degradation that include increased pavement maintenance costs, increased user costs (vehicle repair and operation); increased pavement rehabilitation costs, and loss of serviceability/service life [5]. It is recommended that crack maintenance be conducted from 40° F-75° F to ensure cracks have expanded fully [4], [7], [8].

A.2 Best Practices

Treating cracks in asphalt pavements is a major part of every pavement operation and maintenance program; effective practices for crack sealing start well before sealant/fill application and carries through all the way until the crews and equipment are back in the yard, readying for the next job [9]. While crack seal/fill quality is crucial, the efficiency and safety of pavement maintenance activities must also be prioritized. Efficient crack sealing/filling can be achieved through devotion to optimizing the factors listed above. Best practices for an effective asphalt pavement crack maintenance program include providing detailed and consistent training to crews, pre-testing sealants before use, maintaining tight material controls consistent with manufacturer specifications, and ensuring all equipment is well-maintained and cleaned during its service life [1]. A breakdown of the main crack sealing best practices to increase crew efficiency and seal quality is provided below [9] [10] [11] and [12]:

1. Installation Timings

Crack sealing is a fundamental practice for maintaining pavement longevity, and the timing and conditions of installation are critical factors in achieving optimal results. Spring and fall are the best seasons for crack sealing, as moderate temperatures provide a suitable environment for the installation. Moreover, ambient temperature should be maintained between 40° F-75° F, while the absence of fog and dew during installation is paramount [10] [11]. Furthermore, the pavement condition plays a vital role in the effectiveness of crack sealing. Pavements that are in good condition, with low to moderate crack density and limited branching are optimal candidates for crack sealing, as shown in figure A.1. It is cost-effective to apply crack sealing to pavements with a Pavement Condition Rating (PCR) between 66 and 80.

A.1 Pavements with low to moderate crack density.

Some studies suggest the computation of the Random Cracking Index (RCI) for flexible and composite pavements. The RCI encompasses all random cracks, including thermal transverse,

reflective transverse, longitudinal block, and cement-treated reflective cracks. The RCI is computed using the formula as follows:

$$\boldsymbol{RCI = \ Min\{100, Max\ (0, 100 - DPL - DPM - \ DPH)\}} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (\mathbf{1})$$

Where DP denotes the deduct point due to random cracks, and subscripts L, M, and H represent low, medium, and high severity of the cracks, respectively.

It is crucial to avoid crack sealing on Asphalt Concrete (AC) overlays with an RCI greater than 90. However, when the RCI is between 81 and 89, and preferably between 81 and 85, crack sealing should be applied to achieve optimal results. Moreover, crack seal can be applied when the RCI is between 77 and 69. Thus, considering the installation timing and pavement condition can ensure the effectiveness of the crack sealing practice.

2. *Installation Preparation*

2.1 Crack Cleaning and Drying

Effective preparation of the pavement crack before sealing is essential for the success of crack sealing. Crack cleaning and drying is the most important phase of a success crack sealing [12] [13]. If channels are wet or dirty, it may result in adhesion failure between the sealer material and the sidewall of the crack. Several methods, including high-pressure air blasting, hot air lance (HAL), sand blasting, and wire brushing can be used for cleaning and drying the cracks as shown in Figure A.2.

A.2 Methods for cleaning and drying the pavement cracks.

An air compressor with a minimum of 60 cmfm and 150 psi can be utilized to prepare a crack. However, the hot air lance is more effective in cleaning and drying wet cracks than conventional air compressors. Incorporating the hot air lance in the wet condition is

recommended to extend the operable time and seasonal availability for crack filling and sealing construction [12].

2.2 Removing Vegetation

The presence of vegetation growing in a crack will inhibit the proper performance of the sealant. Therefore, herbicides should be applied to the crack at least two weeks before the crack sealing operation to remove vegetation.

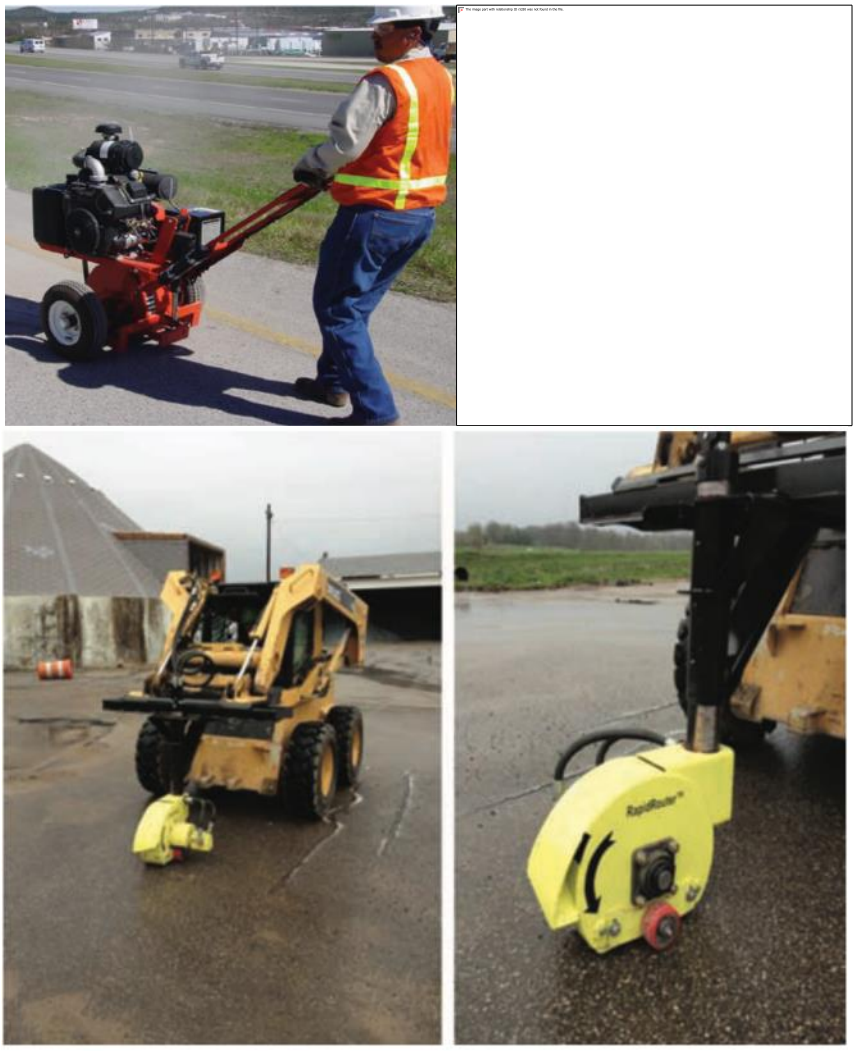
A.3 Pavement crack vegetation.

2.3 Crack Routing

Crack routing is a process used to open the crack to accommodate enough sealant to provide an effective seal, even after the pavement crack opens due to contraction at low temperatures during the winter months. This process also helps to remove sand, rocks, vegetation, debris, and old, oxidized asphalt in the crack, resulting in a sound crack face that allows for better adhesion of the sealant [12].

Routing is typically performed on transverse cracks "working" and greater than 1/8" in width before crack sealing. According to Ponniah and Kennepohl (2007), routing cracks between 1/8" and 3/4" wide is recommended. Although routing is the most time-consuming method of crack preparation, studies suggested that it can double the service life and crack seals compared to cleaning via compressed air, resulting in better performance and return on investment. It is important to note that routing may be detrimental to pavements over six years old due to the aging of the mixture [9].

Crack routing can be performed either manually or using Rapid Router (RR). the use of the Rapid Router (RR) method has several advantages over manual routing [12]. First, it is safer for operators, as it eliminates the need for workers to be close to moving equipment. Secondly, operation speed can be maintained throughout the process, leading to increased efficiency and productivity. Lastly, the RR method does not require as much physical labor as manual routing. These benefits make the RR method a preferable option for crack routing in pavement maintenance operations [12].



A.4 Rapid Router.

3. Care of Sealant Material

It is crucial for crack sealing equipment and materials to be properly maintained before storage. If crack sealing operations resume in the next 1-3 days, the first step is to take care of the material still left in the tank. The manufacturer's recommendations must be followed to ensure materials are properly cooled at the end of the day to prevent coking inside the tank [9]. It is recommended to leave the material tank half full (or full just above the top of the agitator blades to enable the material to heat quicker for the next shift and provide room to add new material. Most manufacturers recommend reheating material only one time; initial heating demobilizing, then reheating the next shift. Leaving room in the tank and adding fresh material will also provide rejuvenation of older material. Heaters may also be used to help shorten the heat time the next shift. These maintenance heaters keep the material at roughly 180°F, cutting heat time by as much as 50%. Pot life is still a concern

and fresh material should be added every 12-15 hours. It should be noted that maintenance heating for more than 8-12 hours will lead to breakdown of the sealant that may result in gelling. If gelling occurs, the entire tank must be shut down, cooled, and cleaned along with all hoses, pumps, and the tank interior – a significant waste of time [9].

4. Equipment Preparation

In addition to material preparation, each crack sealing machine should have its own daily checklist, and crews should work through the checklist at the end of each day. Any problems discovered should be communicated to the crew leader and maintenance staff immediately so they can be fixed overnight. Standard checklist items should include checking the oil and grease points, blowing out and checking filters, and making a visual inspection of the sealing hose, wand, connections, sealant tank and pump. If the crew is using routers, inspect the router bits, blow out the filters and the radiator, and check the oil and grease points. A daily trailer inspection sheet should also be used. While a daily deep cleaning of all equipment is not required, keeping the unit as clean as possible helps it last longer and operate properly [9].

5. Trailer Stocking

Stocking the appropriate amount of material for a work shift is crucial to maximize time sealing and minimize downtime. Loading 10-15% more material than expected is a good rule of thumb as crack size and depth varies and cracks can widen or deepen between the time of the estimate and the work. Crews should fill all fuel tanks, ensure the trailer has all the tools that might be needed on the job in good working order, and check quantities of consumables and wear parts such as tips, switches, fuses to get through the day without a delay [9].

6. Material Handling on the Job

Proper material handling can make crews more productive while improper material handling can not only reduce the on-the-job efficiency but can result in a poor-quality job. Crews should load the tank about three-quarters full before heading to the jobsite in the morning and be allowed to heat during staging area setup and final preparation for operations. Proper application temperature is crucial for ease of application, adhesion, and bonding. To maintain sealant temperature, fresh material should be added equal to the amount of material being applied. It should be noted that adding a block of sealer to the melter lowers the temperature of the molten material, which affects the application temperature. If too much material is added to the tank at once, the cold blocks of unmelted material will cool the material in the tank and drop the temperature, causing crews to stop and wait for the temperature to rise again. Adding equal amounts of material as being placed is the key to maintaining application temperatures and productivity [9].

7. Installation

A successful crack sealing installation requires careful attention to the application process. First, the nozzle of the applicator should be positioned in a way that allows the crack to be filled from the bottom up, minimizing the entrapment of air and ensuring the sealant reaches the proper level. The process should be conducted in a continuous motion along the entire length of the crack, with additional sealant reapplied to areas where the initial application was insufficient or settled. Any bubbling that occurs during application indicates the presence of moisture in the crack and additional drying is needed. Finally, it is essential to use the appropriate applicator wand tip for the specific sealant configuration being used [9].

8. After installation

Proper care after the installation of crack sealant is crucial to ensure its longevity and effectiveness. To allow for complete curing, it is essential to keep traffic off the sealed area until it is fully cured, typically taking 30 minutes to an hour. However, in certain conditions where immediate access is necessary, blotting materials such as blotter sand, release agent, and plastic/paper should be utilized to protect the sealant from damage.

A.5 Traffic is kept off the crack sealant after installation

9. Road Safety

The most dangerous application of pavement crack sealing is active roadway operations. Even with partial closures, crack sealing maintenance crews are exposed to many hazards; traffic, hot temperatures, heavy machinery, and chemical exposure [9]. Minimizing the exposure to these hazards can be done with the appropriate foresight. The appropriate number of traffic control personnel should always be utilized. Additionally, an appropriately sized crew will make operations run efficiently without overcrowding and unnecessary traffic exposure. Excluding traffic control and the job leader, the on-road crack sealing crew should include four personnel:

- Operator of the melter.
- Driver of the two-vehicle.
- Operator of the skid-mounted compressor.
- 1-2 utility personnel (adds blocks to kettle, operates a squeegee if required, provides a safety set of eyes on his peers).

These four members should rotate positions throughout the day to reduce fatigue, and the leader should fill in where required. The leader should always come to the job site with a prepared plan of action for the day's activity. All breaks and stops should be planned. Never stop at an intersection, for example, work through dangerous areas, then break.

A.3 Emerging Technologies

Even when best practices are implemented effectively, crack sealing programs are subject to challenges. Road crews will never be completely safe from the inherent danger involved with working on active highways. Additionally, many agencies utilize on-the-job training for their personnel which lacks uniformity and can lead to inconsistent applications. Improper or inconsistent crack routing, cleaning, and sealing is a common occurrence due to the delicate nature of cracked asphalt and limited crews rushing to complete too much work [1]. Finally, the labor-intensive nature of crack sealing not only leads to greater elevated risk traffic exposure but also means that 60-80 percent of crack sealing cost is labor [9], [14].

Emerging technologies show promise for improving the quality, efficiency, and safety of pavement crack sealing. Certain best practices such as vehicle maintenance and preparation will remain manual tasks, however, automation can be applied to material handling and crack identification, cleaning, and sealing. The use of autonomous and semi-autonomous technologies applied to pavement crack sealing could make operations safer, more consistent, and faster which will both reduce cost and risk to drivers and maintenance crews. As autonomous and deep learning technologies continue to be applied to the transportation infrastructure sector at large [15]–[18], it is logical to assume this trend will apply to infrastructure maintenance as well.

While research is limited, the application of autonomous robotics to pavement sealing should, in theory, take crack data from an external sensor, extract connected crack paths, and link those paths to plot the motion a robotic system can seal the crack [19]. Real-world testing has shown that robotic crack sealing systems can successfully seal pavement cracks with sealant on real roadways with reduced risk to maintenance crews [20]. As early as 1992, a feasible prototype was fielded using an XY-table manipulator for sealant application combined with vision and range sensos for crack mapping to autonomously seal pavement cracks [14]. In 2012, researchers at the

Georgia Institute of Technology (GT) developed a successful proof-of-concept prototype that could detect of 83% of cracks at a level of 90% or better with 15% false positive response [21]. During road tests, the GT system detected cracks smaller than one-eighth-inch wide and efficiently filled cracks from a vehicle moving at three miles per hour. The trailer mounted prototype consisted of a stereo camera, light-emitting diodes (LEDs) of two distinct colors, and an assembly to provide a continuous supply of sealant to longitudinal and transverse sealant distribution systems. The operation was based on the contrasting information produced by LEDs with a thresholding and filtering algorithm generating a map of any cracks (≥3 mm) to guide an array of twelve sealant nozzles. The GT system could operate at a speed of up to 3 mph (4.8 km/h) and required only one worker to drive the vehicle pulling the trailer, as shown in Figure A.6. While the GT system was a successful proof-of-concept, issues with the computer vision system and associated algorithm limited performance. Another issue is its inconsistent performance on dark pavement with high contrast. Moreover, insufficient crack cleaning is one of the system's issues. Additionally, the sealant supply mechanism of the GT system required refinement to achieve the required results.

A.6 Simi-autonomous crack sealing technology (*21*).

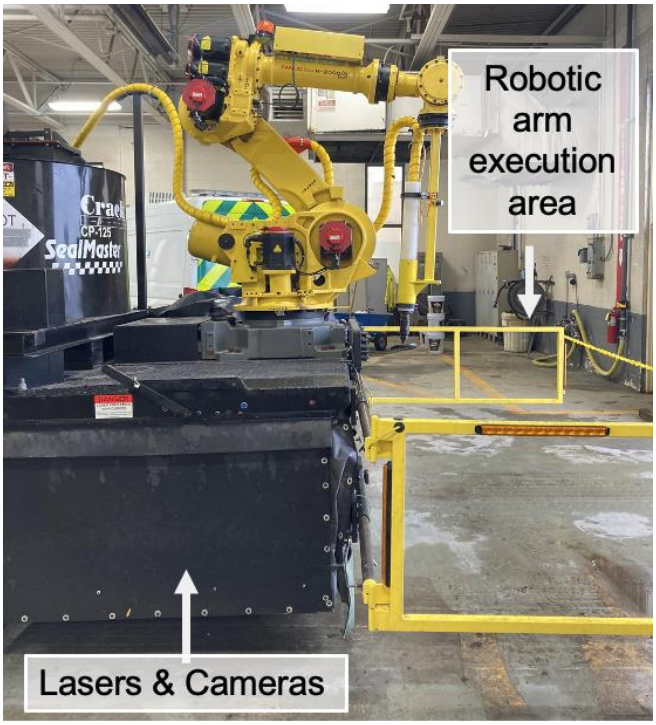
In 2013, the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center successfully introduced crack sealing equipment capable of high production automated longitudinal sealing and enhanced manual in-lane crack sealing operations into California's Caltrans statewide maintenance operations [22]. The Sealzall prototype was operated by Caltrans District 11 crews for a one-year trial period where the machine provided a sixfold increase in longitudinal sealing production rate while eliminating direct worker traffic exposure. Sealzall longitudinal crack sealing is conducted via continuous, fast-moving lane closures during which no workers are directly exposed to traffic on the highway. While not fully autonomous, the Sealzall showed an impressive, field-tested proof-of-concept that improves production and safety that saved the state of California $4 million over the span of the one-year implementation [22]. Due to the semi-autonomous nature of the AHMCT Sealzall, the system still requires a driver to control the nozzle and is unable to fill in-lane cracks automatically making the in-lane, or transverse, crack repair process labor-intensive. To remedy this drawback, in 2022, researchers are the Nottingham Transportation Engineering Center demonstrated a machine process to repair cracks in asphalt pavements by filling them with hot bitumen via automated three-dimensional (3D) printer [23]. While only laboratory testing has been conducted thus far, 3D printed asphalt pavement crack sealing was shown to be possible and initial shear strength and porosity of 3D printed seals were characterized relative to manual processes. Additionally, the variables of bitumen flow, filling speed, and width/depth of cracks were identified as key determinants of crack seal quality that must be carefully controlled in the future.

Concurrent with ongoing research, the New Mexico Department of Transportation (NMDOT), Indiana Toll Road Authority, the United States Air Force (USAF), and Axtell's Incorporated (a multi-national airfield pavement maintenance company) are considering adopting or have adopted a system made by Robotic Maintenance Vehicles (RMV) [24]. The RMV is the only commercially available solution for semi-autonomous crack sealing capable of both longitudinal and transverse crack sealing. As shown in the following figures, The RMV consists of a truck-mounted Fanuc six-axis R2000 robotic arm, a SealMaster CrackPro 260 sealing unit, an air blow-off system to remove road debris with a high-resolution automated computer vision system to find and measure the cracks [26]. The United States Air Force (USAF) has also taken an interest in automated pavement repair and in 2021, the USAF awarded contracts to the company necoTECH that will pilot the RMV at two bases in the United States [29]. In a demonstration provided by RMV to the Ohio Department of Transportation on 1 November 2022, it was made clear that several improvements to the final production model of the RMV would be made to improve performance: (1) all production RMV systems will be built upon a new F-550 (or equivalent) chassis, (2) the blower motor and diffuser bar will both be upgraded in production to allow for easier height/angle adjustment while using 15 CFM versus the 10 CFM, (3) range of motion for the robotic arm will be 12ft for the production model, and (4) crack sealant application efficiency (quantity and penetration) was improving steadily as they receive data from continued testing and demonstrations for algorithm training. The system has potential to increase the speed and quality of pavement crack sealing while improving safety and saving money through lower labor requirements and worker hazard exposure [27].

A.7 Sealzall System developed by (AHMCT) (*22*)

A.8 RMV crack sealer.

A.9 RMV Prototype vehicle in ODOT D3 garage.



A.10 RMV crack sealer robotic arm execution area and laser/camera locations.

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Appendix B

Survey Questionnaires

C.1 Introduction

As a part of this research study, two surveys were conducted to gather information on crack sealing practices from transportation agencies in Ohio and other states to supplement the results of the literature review. Some questions on the survey questionnaires were designed to document the current state-of-the-practice and recommended best practices for crack sealing. Other questions were designed to help the research team identify cost-effective and reliable new equipment and technologies that can help improve the efficiency of crack sealing installation and enhance the safety of employees involved in the installation process. The first survey was sent to the Ohio Department of Transportation (ODOT) district offices and county garages. The second survey was a national survey that targeted transportation agencies in other states in the United States.

C.2 ODOT Survey

A draft survey questionnaire for ODOT personnel was prepared by the research team and sent to the Technical Advisory Committee (TAC) for this research task at the beginning of October of 2022. The survey invitation was forwarded by the advisory committee to the different ODOT Districts, and the due date for completing the survey was November 4, 2022.

The questionnaire included a total of 22 questions and was organized as follows. On the landing screen, an introduction was provided to inform the respondents of the purpose of the survey, the expected amount of time required to complete the survey, and the option to download the survey as a .pdf file. In addition, the respondents were given contact information for the Principal Investigator (PI) and the Co-PI for the project, should the respondents have any questions regarding the survey (Question 1 (Q1)).

In the first section of the survey, respondents were asked to provide their contact information to be used for follow-up purposes if needed (Q2). In the second section (General Information), respondents were asked if their district/county uses crack sealing for pavement preservation (Q3).

For agencies that currently use crack sealing, the respondents were asked if the crack sealing for their county is performed by an in-house crew or external contractors (Q4), what criteria are used for selecting roads for crack sealing (Q5), their agency's annual budget for crack sealing (Q6), and what months of the year the agency performs crack sealing. In the third section, the respondents were asked about the crack cleaning and preparation methods used prior to crack sealing (Q8), the type of equipment used in their county (Q9), how satisfied they are with automated/robotic crack sealing equipment (if used; Q10), the type of material used (Q11), the application methods (Q12), and how satisfied they are with the overall quality of installation (Q13). The fourth section focused on the performance of the crack sealing, asking respondents to rate the importance of various factors on the performance (Q14), what crack sealing distresses are commonly encountered in their county (Q15), the typical service life for crack sealing in their county (Q16), and how effective the crack sealing is in extending the service life of the pavement surface (Q17). The fifth section asked about issues encountered during crack sealing (Q18), recommendations for best practices to improve the performance of the crack sealing (Q19), and final thoughts or comments that the respondents would like to share with the research team that might benefit the research project (Q20).

Respondents who indicated in their response to Question 3 that their agencies used crack sealing in the past but are no longer using it were asked to elaborate on why their county stopped using it (Q21) and were asked for permission for the research team to contact them to obtain follow-up information, if needed (Q22). For the individuals who indicated in their responses to Q3 that their agencies have never used crack sealing, this was the end of the survey. On the last screen of the survey, the respondents were thanked for their time and effort. A copy of the ODOT survey questionnaire is provided below.

ODOT Survey

Q1 Best Practices for Crack Sealing

This survey is conducted to document the current state-of-the-practice and recommended best practices for crack sealing. It also aims to identify cost-effective and reliable new equipment and technologies that can help improve the efficiency of crack sealing installation and enhance the safety of ODOT employees involved in the installation process.

The survey should take less than 15 minutes to complete. Please complete the survey even if your county does not use crack sealing. If your county does not use crack sealing, the survey should take less than one minute to complete.

To view the survey questionnaire as a pdf file, please click: survey file.

For questions about this survey, please contact:

Dr. Munir Nazzal
Department of Civil and Architectural Engineering and Construction Management
The University of Cincinnati
Email: munir.nazzal@uc.edu
or: Dr. Ala R. Abbas Department of Civil Engineering
The University of Akron
Email: abbas@uakron.edu

Q2 Contact Information: *

- Name: (1) _____
- Position: (2) _____
- District: (3) _____
- County: (4) _____
- Email address: (5) _____
- Phone number: (6) _____

Q3 Does your county use crack sealing for pavement preservation? *

- Yes, we currently use crack sealing. (1)
- No, we used crack sealing in the past, but we no longer use it. (2)
- No, we have never used crack sealing. (3)

Q4 Crack sealing is performed by (check all that apply): *

- [ ] In-house crew (1)
- [ ] External contractors (2)

Q5 What criteria are used for selecting roads for crack sealing (check all that apply):

- [ ] Type of road (interstate, arterial, collector, local) (1)
- [ ] Traffic level (5)
- [ ] Type of pavement (flexible or rigid) (6)
- [ ] Age since construction (7)
- [ ] Type of cracks (8)
- [ ] Crack width (9)
- [ ] Other. Please specify: (2)

_____

Q6 What is your annual budget for crack sealing?

- ○ Less than or equal to $50,000 (3)
- ○ More than $50,000 and less than or equal to $150,000 (5)
- ○ More than $150,000 and less than or equal to $500,000 (1)
- ○ More than $500,000 (2)

Q7 When is crack sealing performed during the year by your county (check all that apply)?

- [ ] January (7)
- [ ] February (8)
- [ ] March (9)
- [ ] April (10)
- [ ] May (11)
- [ ] June (19)
- [ ] July (12)
- [ ] August (13)
- [ ] September (14)
- [ ] October (15)
- [ ] November (16)
- [ ] December (17)

Q8 Which of the following crack cleaning and preparation methods have been used by your county prior to crack sealing (check all that apply)? *

- [ ] Compressed air (1)
- [ ] Routing of cracks (2)
- [ ] Hot air lance (3)
- [ ] Sawing (4)
- [ ] Wire brush (5)
- [ ] Pressurized water (6)
- [ ] Sand blasting (7)
- [ ] None of the above (8)

Q9 What type of crack sealing equipment is used by your county (check all that apply)? *

- [ ] Small walk behind. Please provide manufacturer name: (6) _____
- [ ] Tow-behind. Please provide manufacturer name: (7) _____
- [ ] Automated/robotic (e.g., https://rmv.llc/). Please provide manufacturer name: (8) _____
- [ ] Other. Please specify and provide manufacturer name: (9) _____

Q10 How satisfied are you with your automated/robotic crack sealing equipment?

- ○ Very satisfied (1)
- ○ Somewhat satisfied (2)
- ○ Not satisfied. Please elaborate on the reasons for dissatisfaction: (3) _____

Q11 What type of material is used by your county for crack sealing (check all that apply)?

- [ ] Hot-applied. Please provide most common type(s) and source(s): (1) _____
- [ ] Cold-applied. Please provide most common type(s) and source(s): (2) _____
- [ ] I don't know (3)

Q12 Which of the following application methods are used by your county for crack sealing (check all that apply)?

- [ ] Recessed (Figure 1) (3)
- [ ] Flush non-routed (Figure 2 left) (11)
- [ ] Flush routed (Figure 2 right) (12)
- [ ] Overband non-routed (Figure 3 left) (13)
- [ ] Overband routed (Figure 3 right) (14)

Q13 How satisfied are you with the overall quality of installation for crack sealing in your county?

- ○ Very satisfied (1)
- ○ Somewhat satisfied (2)
- ○ Not satisfied. Please elaborate on the reasons for dissatisfaction: (3) _____

Q14 Rate the importance of the following factors on the performance of crack sealing:

	Insignificant (7)	Somewhat Significant (8)	Highly Significant (9)
Application equipment (1)	○	○	○
Training of installation crew (22)	○	○	○
Type of crack sealant (23)	○	○	○
Use of crack routing prior to installation (24)	○	○	○
Crack cleaning prior to installation (25)	○	○	○
Application method (recessed, flush, or overband) (26)	○	○	○
Over- or under-application of crack sealant (27)	○	○	○
Application temperature of sealant (for hot-applied) (28)	○	○	○
Air and pavement temperatures during installation (29)	○	○	○
Presence of moisture on pavement surface (30)	○	○	○
Contamination by deicing products (31)	○	○	○
Precipitation rate during installation (32)	○	○	○
Precipitation rate after installation (33)	○	○	○
Type of crack to be sealed (34)	○	○	○
Crack width prior to sealing (35)	○	○	○
Timing of cracking sealing after pavement construction or placement of overlay (36)	○	○	○

Q15 Which of the following crack sealing distresses are commonly encountered in your county (check all that apply)?

- [ ] Pull out by vehicles (1)
- [ ] Tracking by vehicle tires (2)
- [ ] Adhesive failure (or lack of bonding) (7)
- [ ] Cohesive failure (e.g., tear of crack sealant) (9)
- [ ] Raveling of crack (10)
- [ ] Spalling of crack (11)
- [ ] Other. Please specify: (3)

_____

Q16 What is the typical crack sealing service life in your county?

- ○ Less than two years (1)
- ○ Two to four years (2)
- ○ Four to six years (10)
- ○ More than six years (11)

Q17 How effective is crack sealing in extending the service life of a pavement surface? *

- ○ Very effective (pavement surface life is extended by more than three years) (1)
- ○ Somewhat effective (pavement surface life is extended by one or two years) (10)
- ○ Ineffective (11)

Q18 Has your county encountered any of the following issues during crack sealing (check all that apply)? *

- [ ] Equipment failure (1)
- [ ] Worker injury (2)
- [ ] Damage to crack sealing equipment by traffic (7)
- [ ] Reported damage to other vehicles by crack sealing crew (9)
- [ ] Reported damage to adjacent properties by crack sealing crew (10)
- [ ] Other. Please specify: (11) _____
- [ ] None of the above (3)

Q19 Any recommendations for best practices to improve the performance of crack sealing (recommended installation procedure, recommended crack sealing material types, etc.)?

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Q20 Any final thoughts or comments that you would like to provide that may benefit this research project? Please send any documents that might be helpful to this project to Dr. Ala Abbas by email at abbas@uakron.edu.

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Q21 Please elaborate on why your county stopped using crack sealing.

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Q22 Do we have your permission to contact you in the future (if needed) for more information regarding your responses? *

- ○ Yes (1)
- ○ No (10)

C.3 National Survey

A draft survey questionnaire for the national survey was prepared by the research team and sent to the Technical Advisory Committee (TAC) for this research task at the end of October of 2022. The survey invitation was sent out by ODOT Office of Statewide Planning & Research on November 4, 2022, and the due date for completing the survey was December 8, 2022.

The questionnaire included a total of 22 questions – mostly similar but some questions were different than the ODOT survey – and was organized as follows. On the landing screen, an introduction was provided to inform the respondents of the purpose of the survey, the expected amount of time required to complete the survey, and the option to download the survey as a .pdf file. In addition, the respondents were given contact information for the Principal Investigator (PI) and the Co-PI for the project, should the respondents have any questions regarding the survey (Question 1 (Q1)).

In the first section of the survey, respondents were asked to provide their contact information to be used for follow-up purposes if needed (Q2). In the second section (General Information), respondents were asked if their agency uses crack sealing for pavement preservation (Q3).

For agencies that currently use crack sealing, the respondents were asked if the crack sealing for their county is performed by an in-house crew or external contractors (Q4), what criteria are used for selecting roads for crack sealing (Q5), and their agency's annual budget for crack sealing (Q6). In the third section, the respondents were asked specific questions about the installation: the crack cleaning and preparation methods used prior to crack sealing (Q7), the type of equipment used in their county (Q8), if their agency has ever used or experimented with automated/robotic crack sealing equipment (Q9), how satisfied they are with automated/robotic crack sealing equipment (if used; Q10), the type of material used (Q11), the application methods (Q12), and how satisfied they are with the overall quality of installation (Q13). The fourth section focused on the performance of the crack sealing, asking respondents to rate the importance of various factors on the performance (Q14), what crack sealing distresses are commonly encountered in their jurisdiction (Q15), the typical service life for crack sealing in their jurisdiction (Q16), and how effective the crack sealing is in extending the service life of the pavement surface (Q17). The fifth section asked about issues encountered during crack sealing (Q18), recommendations for best practices to improve the performance of the crack sealing (Q19), and final thoughts or comments that the respondents would like to share with the research team that might benefit the research project (Q20).

Respondents who indicated in their response to Question 3 that their agencies used crack sealing in the past but are no longer using it were asked to elaborate on why their county stopped using it (Q21) and were asked for permission for the research team to contact them to obtain follow-up information, if needed (Q22). For the individuals who indicated in their responses to Q3 that their agencies have never used crack sealing, this was the end of the survey. On the last screen of the survey, the respondents were thanked for their time and effort. A copy of the national survey questionnaire is provided below.

National Survey

Q1 Best Practices for Crack Sealing (National Survey)

This survey is conducted to document the current state-of-the-practice and recommended best practices for crack sealing. It also aims to identify cost-effective and reliable new equipment and technologies that can help improve the efficiency of crack sealing installation and enhance the safety of ODOT employees involved in the installation process.
The survey should take less than 10 minutes to complete. Please complete the survey even if your agency does not use crack sealing. If your agency does not use crack sealing, the survey should take less than one minute to complete.
To view the survey questionnaire as a pdf file, please click: survey file.

For questions about this survey, please contact:
Dr. Munir Nazzal
Department of Civil and Architectural Engineering and Construction Management
The University of Cincinnati
Email: munir.nazzal@uc.edu
or: Dr. Ala R. Abbas Department of Civil Engineering
The University of Akron
Email: abbas@uakron.edu

Q2 Contact Information: *

- ○ Name: (1) _____
- ○ Position: (2) _____
- ○ Agency: (3) _____
- ○ State: (4) _____
- ○ Email address: (5) _____
- ○ Phone number: (6) _____

Q3 Does your agency use crack sealing for pavement preservation? *

- ○ Yes, we currently use crack sealing. (1)
- ○ No, we used crack sealing in the past, but we no longer use it. (2)
- ○ No, we have never used crack sealing. (3)

Q4 Crack sealing is performed by (check all that apply): *

- ☐ In-house crew (1)
- ☐ External contractors (2)

Q5 What criteria are used for selecting roads for crack sealing (check all that apply):

- [ ] Type of road (interstate, arterial, collector, local) (1)
- [ ] Traffic level (5)
- [ ] Type of pavement (flexible or rigid) (6)
- [ ] Age since construction (7)
- [ ] Type of cracks (8)
- [ ] Crack width (9)
- [ ] Other. Please specify: (2)

Q6 What is your agency's annual budget for crack sealing?

- ○ Less than or equal to $50,000 (3)
- ○ More than $50,000 and less than or equal to $150,000 (5)
- ○ More than $150,000 and less than or equal to $500,000 (1)
- ○ More than $500,000 (2)

Q7 Which of the following crack cleaning and preparation methods have been used by your agency prior to crack sealing (check all that apply)? *

- [ ] Compressed air (1)
- [ ] Routing of cracks (2)
- [ ] Hot air lance (3)
- [ ] Sawing (4)
- [ ] Wire brush (5)
- [ ] Pressurized water (6)
- [ ] Sand blasting (7)
- [ ] None of the above (8)

Q8 What type of crack sealing equipment is currently being used by your agency (check all that apply)? *

- [ ] Small walk behind. Please provide manufacturer name: (6) _____
- [ ] Tow-behind. Please provide manufacturer name: (7) _____
- [ ] Automated/robotic (e.g., https://rmv.llc/). Please provide manufacturer name: (8) _____
- [ ] Other. Please specify and provide manufacturer name: (9)

Q9 Has your agency every used or experimented with using an automated/robotic crack sealing equipment? *

- ○ No (1)
- ○ Yes. Please provide the manufacturer name: (3)

Q10 How satisfied are you (or were you) with the automated/robotic crack sealing equipment?

- ○ Very satisfied (1)
- ○ Somewhat satisfied (2)
- ○ Not satisfied. Please elaborate on the reasons for dissatisfaction: (3)

Q11 What type of material is used by your agency for crack sealing (check all that apply)?

- [ ] Hot-applied. Please provide most common type(s) and source(s): (1) _____
- [ ] Cold-applied. Please provide most common type(s) and source(s): (2) _____
- [ ] I don't know (3)

Q12 Which of the following application methods are used by your agency for crack sealing (check all that apply)?

- [ ] Recessed (Figure 1) (3)
- [ ] Flush non-routed (Figure 2 right) (11)
- [ ] Flush routed (Figure 2 left) (12)
- [ ] Overband non-routed (Figure 3 right) (13)
- [ ] Overband routed (Figure 3 left) (14)

Q13 How satisfied are you with the overall quality of installation for crack sealing in your jurisdiction?

- ○ Very satisfied (1)
- ○ Somewhat satisfied (2)
- ○ Not satisfied. Please elaborate on the reasons for dissatisfaction: (3)

Q14 Rate the importance of the following factors on the performance of crack sealing:

	Insignificant (7)	Somewhat Significant (8)	Highly Significant (9)
Application equipment (1)	○	○	○
Training of installation crew (22)	○	○	○
Type of crack sealant (23)	○	○	○
Use of crack routing prior to installation (24)	○	○	○
Crack cleaning prior to installation (25)	○	○	○
Application method (recessed, flush, or overband) (26)	○	○	○
Over- or under-application of crack sealant (27)	○	○	○
Application temperature of sealant (for hot-applied) (28)	○	○	○
Air and pavement temperatures during installation (29)	○	○	○
Presence of moisture on pavement surface (30)	○	○	○
Contamination by deicing products (31)	○	○	○
Precipitation rate during installation (32)	○	○	○
Precipitation rate after installation (33)	○	○	○
Type of crack to be sealed (34)	○	○	○
Crack width prior to sealing (35)	○	○	○
Timing of cracking sealing after pavement construction or placement of overlay (36)	○	○	○

Q15 Which of the following crack sealing distresses are commonly encountered in your jurisdiction (check all that apply)?

- [ ] Pull out by vehicles (1)
- [ ] Tracking by vehicle tires (2)
- [ ] Adhesive failure (or lack of bonding) (7)
- [ ] Cohesive failure (e.g., tear of crack sealant) (9)
- [ ] Raveling of crack (10)
- [ ] Spalling of crack (11)
- [ ] Other. Please specify: (3)

Q16 What is the typical crack sealing service life in your jurisdiction?

- ○ Less than two years (1)
- ○ Two to four years (2)
- ○ Four to six years (10)
- ○ More than six years (11)

Q17 How effective is crack sealing in extending the service life of a pavement surface in your jurisdiction? *

- ○ Very effective (pavement surface life is extended by more than three years) (1)
- ○ Somewhat effective (pavement surface life is extended by one or two years) (10)
- ○ Ineffective (11)

Q18 Has your agency encountered any of the following issues during crack sealing (check all that apply)? *

- [ ] Equipment failure (1)
- [ ] Worker injury (2)
- [ ] Damage to crack sealing equipment by traffic (7)
- [ ] Reported damage to other vehicles by crack sealing crew (9)
- [ ] Reported damage to adjacent properties by crack sealing crew (10)
- [ ] Other. Please specify: (11) _____
- [ ] None of the above (3)

Q19 Any recommendations for best practices to improve the performance of crack sealing (recommended installation procedure, recommended crack sealing material types, etc.)?

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Q20 Any final thoughts or comments that you would like to provide that may benefit this research project? Please send any documents that might be helpful to this project to Dr. Ala Abbas by email at abbas@uakron.edu.

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Q21 Please elaborate on why your agency stopped using crack sealing.

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Q22 Do we have your permission to contact you in the future (if needed) for more information regarding your responses? *

- ○ Yes (1)
- ○ No (10)

Appendix C
Survey Results

C.1 Introduction

The research team received responses to both the ODOT survey (with responses from ODOT personnel at district offices and county garages) and the national survey (with responses from personnel at departments of transportation and local public agencies). The following sections present a summary of the responses to the two survey questionnaires, organized by topic and presented in the same order as the questions listed in the survey.

C.2 Responses to the ODOT Survey

A total of 46 responses to the ODOT survey were received. Most of the responses were provided by personnel at county garages, but some responses were received by representatives from ODOT district offices.

C.2.1 General Question

The ODOT survey began with a general question to determine if crack sealing is performed by the district or the county. Subsequent questions were asked of respondents who indicated that their agency currently performs crack sealing or had performed crack sealing in the past, and those who indicated that their agencies had never performed crack sealing were directed to the end of the survey and thanked for their time. Below is the question presented in this part of the survey, along with a summary of the responses to this question.

- Does your county use crack sealing for pavement preservation? (Question 3): A summary of the responses regarding the use of crack sealing for pavement presentation in presented in Figure C.1. In this figure, the y-axis indicates a specific response to the question, while the x-axis indicates the number of respondents who chose the specific response. As can be noticed from this figure, 37 (out of 46) respondents indicated that their district or county currently uses crack sealing, eight respondents indicated that their district or county used crack sealing in the past but no longer uses it, and one respondent indicated that their district or county has never used crack sealing. For respondents who indicated that their agency has never used crack sealing, this was the last question on the survey, and the respondents were thanked for their time.

C.2.2 Responses from ODOT districts and counties that perform crack sealing

- Crack sealing is performed by (check all that apply) (Question 3): For the 37 respondents who indicated that their district or county performs crack sealing, more information was solicited about who performs the crack sealing. The survey results, shown in Figure C.2, reveal that 22 respondents reported that crack sealing is performed by an in-house crew, eleven respondents reported that crack sealing is performed by an in-house crew or by external contractors, and four respondents indicated the work is performed by external contractors.

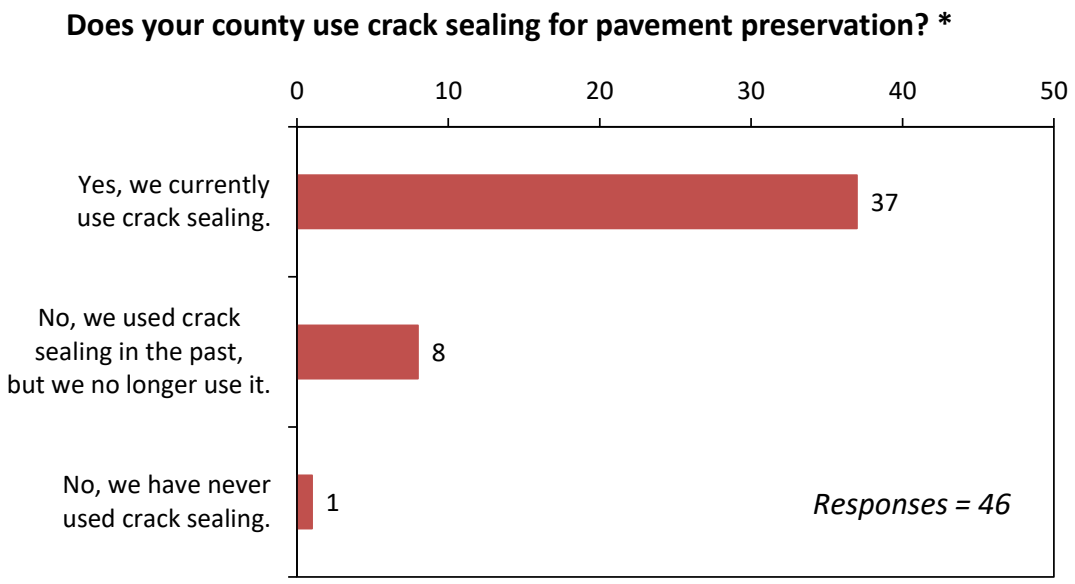

Figure C.1: Use of Crack Sealing for Pavement Preservation by ODOT Districts and Counties.

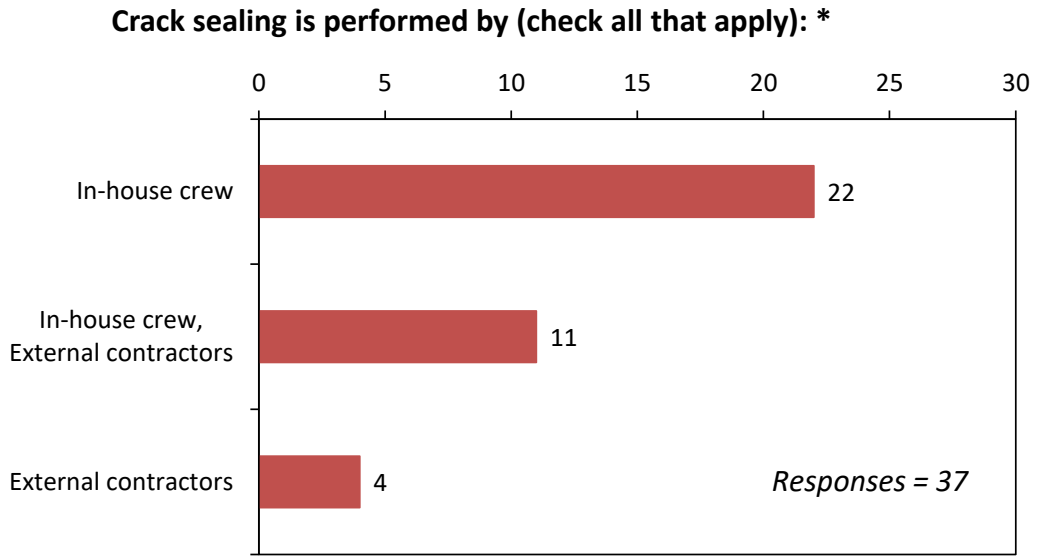

Figure C.2: Percentage of Crack Sealing Performed by In-house Crews and Contractors in Ohio.

- Criteria used for selecting roads for crack sealing (check all that apply) (Question 5): The survey results shown in Figure C.3 indicate that the most common criteria for selecting roads for crack sealing are the crack width, the type of crack, and the age since construction. Less common are the type of road, the type of pavement (flexible or rigid), or the traffic level.

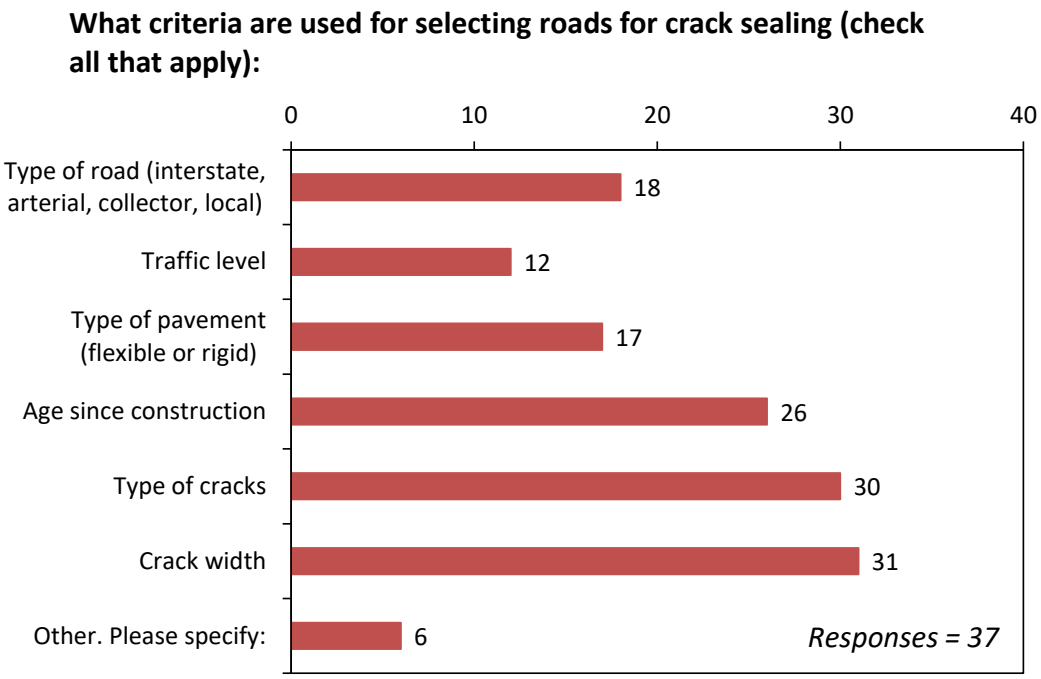

Figure C.3: Criteria Used for Selecting Roads for Crack Sealing in Ohio.

- Annual budget for crack sealing (Question 6): A total of 36 responses were received for this question. A summary of the responses is provided in Figure C.4. When asked about their agency's annual budget for crack sealing, 23 respondents indicated that they spend less than or equal to $50,000 per year, 8 respondents indicated that they spend more than $50,000 but less than or equal to $150,000, and 5 respondents indicated that they spend more than $150,000 but less than or equal to $500,000. No respondents indicated that their agency spends more than $500,000.

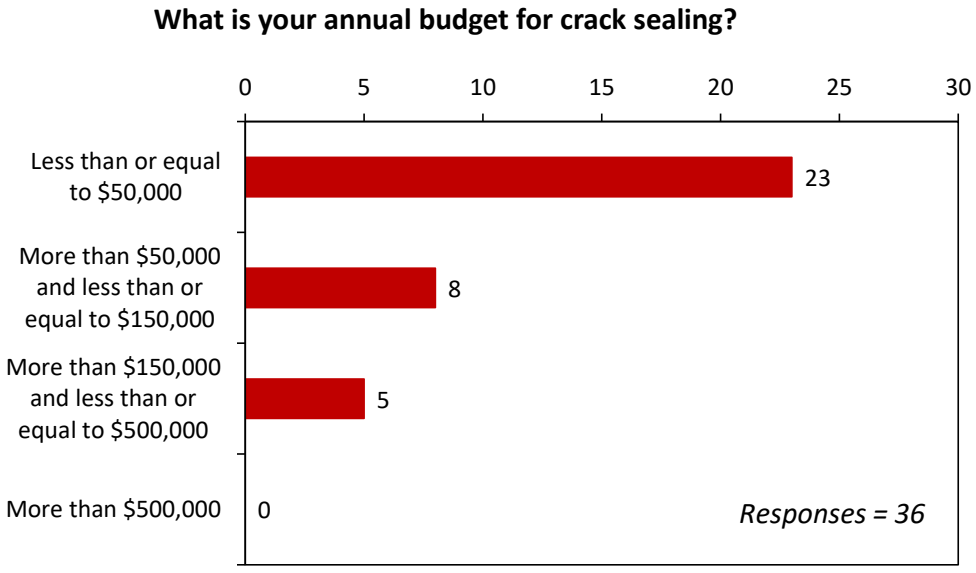

Figure C.4: Annual Budget for Crack Sealing of Agencies in Ohio.

- Months of the year when crack sealing is performed (Question 7): The next question asked respondents to indicate which months of the year when crack sealing is performed. As can be noticed from Figure C.5, crack sealing is most often performed during the spring season (March, April, and May) and autumn months (September, October, and November). Fewer respondents reported that their agencies performed crack sealing during the summer or winter months.

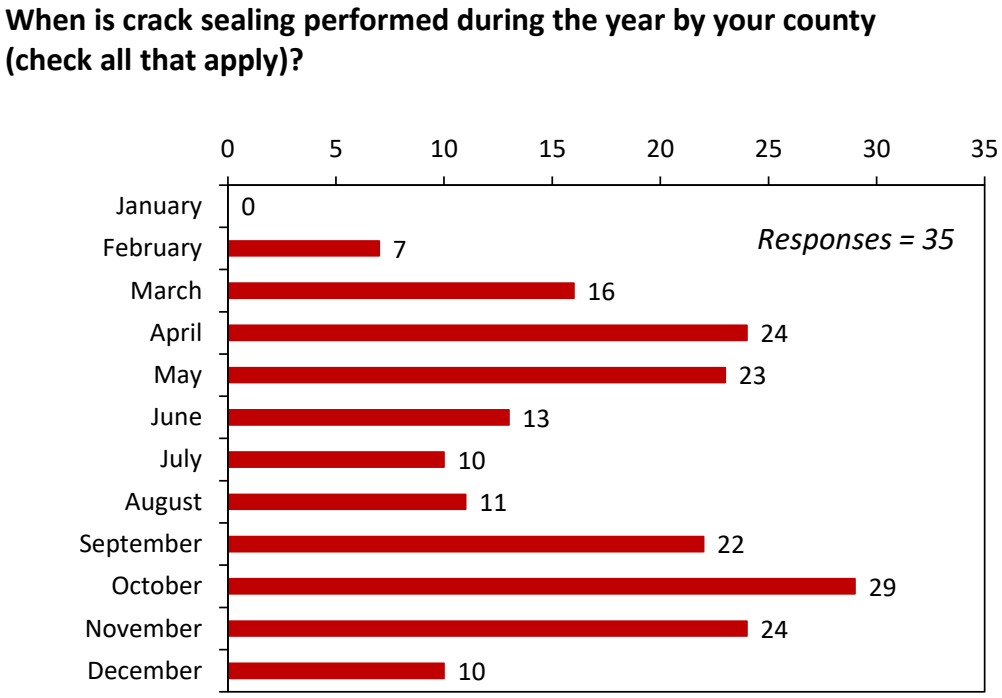

Figure C.5: Months of the Year when Crack Sealing is Performed in Ohio.

- Crack cleaning and preparation methods (Question 8): When asked what crack cleaning and preparation methods have been used by their agency prior to crack sealing, the vast majority of the respondents indicated that cracks are cleaned using compressed air (Figure C.6). Other methods reportedly used were routing, hot air lance, cleaning with a wire brush, and sand blasting. No respondents indicated that they used sawing or cleaning with pressurized water.

- Type of crack sealing equipment used (Question 9): When asked what crack sealing equipment is used by their agency, the vast majority of the respondents indicated that they use a tow-behind unit, a few reported using a small walk-behind unit, and no respondents indicated using automated/robotic equipment or other equipment for this purpose (Figure C.7). Of the different manufacturers mentioned for the tow-behind equipment, the vast majority mentioned Crafco; others included Sealmaster, Ingersoll Rand, DJL, Kimco, YT, and Southeastern Equipment. The respondents reported using small walk-behind units such as Crack Pro Air Compressor, Craft Coat, and Crafco.

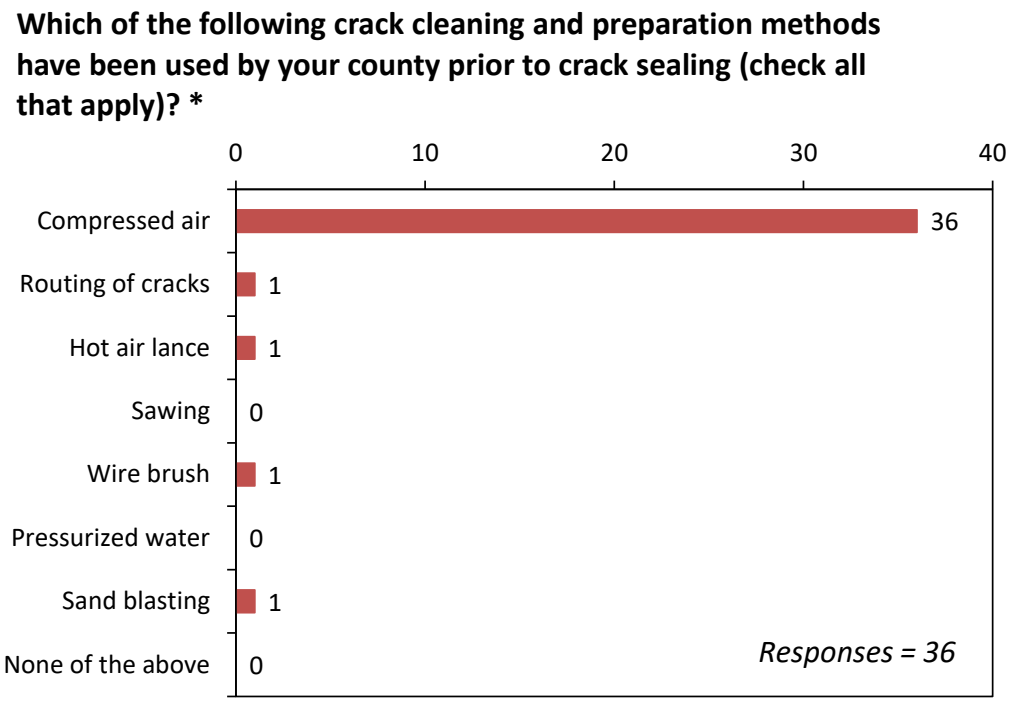

Figure C.6: Crack Cleaning and Preparation Methods used in Ohio.

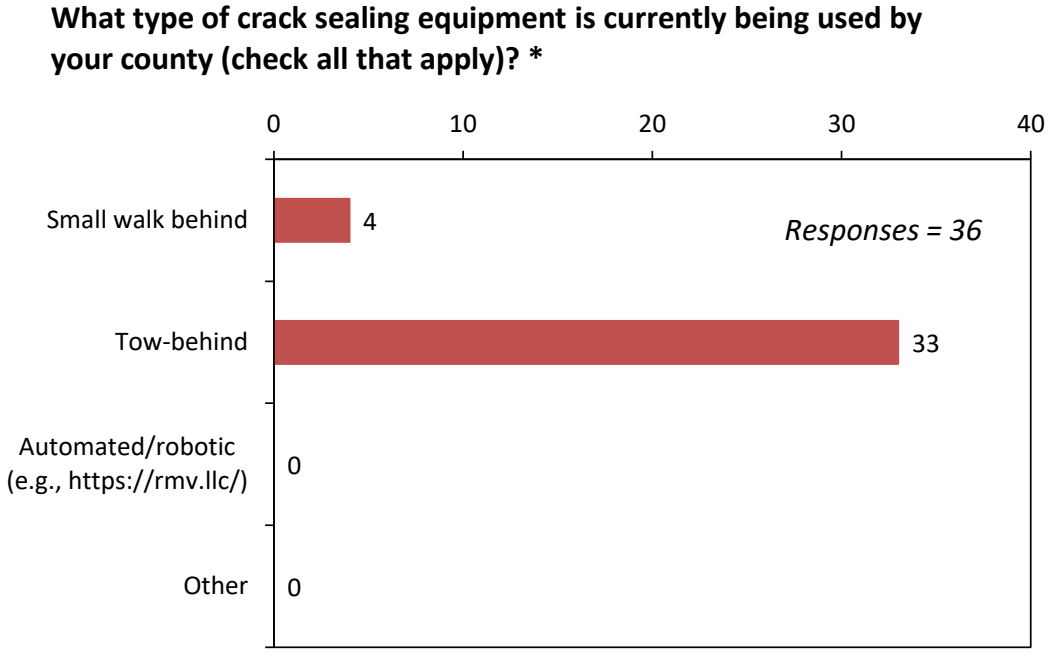

Figure C.7: Crack Sealing Equipment used in Ohio.

- Satisfaction with automated/robotic crack sealing equipment (Question 10): No respondents replied to this question, as none had indicated in their response to Question 9 that they use automatic/robotic crack sealing equipment.

- Type of material used for crack sealing (Question 11): All respondents indicated that their agency uses hot-applied crack sealing materials (Figure C.8). One respondent indicated that cold-applied materials are also used. The respondents mentioned a variety of hot-applied materials. These included Crafco 34540 fiber asphalt sealant 540, Crafco RoadSaver 34515, Crafco 34525, Crack Master PF (Type IV) Polymer Modified Polyester Fiber Sealant, Crafco-515 blocks, DJL material, SealMaster Cracksaver 1190 NR, and block rubber materials. The only cold-applied material that was mentioned was Kold-Flo (which was obtained in five-gallon buckets).

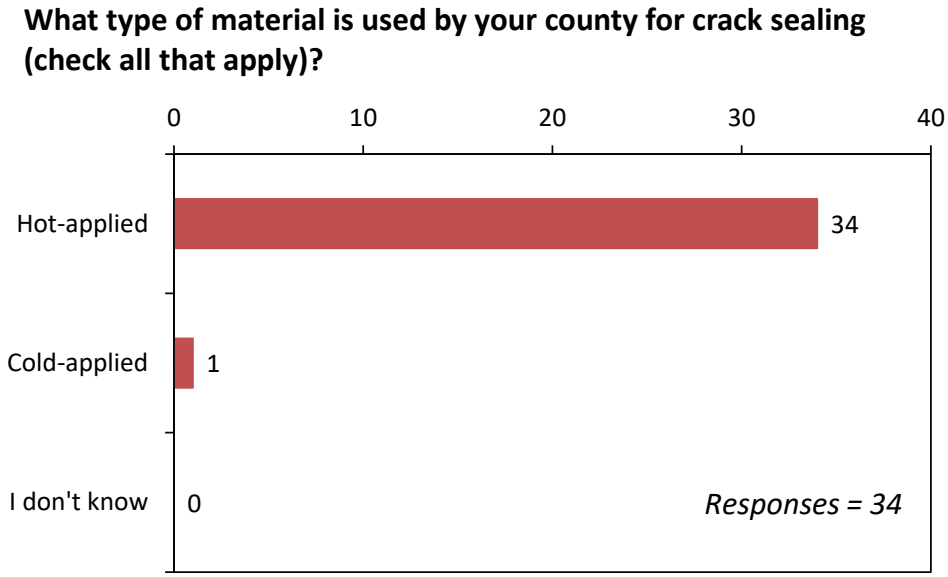

Figure C.8: Type of Material used for Crack Sealing in Ohio.

- Application methods used for crack sealing in Ohio (Question 12): A total of 45 individuals responded to this question. In the responses shown in Figure C.9, the applications are listed along the y-axis and the number of responses is indicated on the x-axis. The most common response was overband non-routed, followed by flush non-routed, recessed, flush routed, and overband routed.

- Satisfaction with the overall quality of crack sealing installation in Ohio (Question 13): A total of 35 individuals responded to this question (Figure C.10). The majority (21 respondents) indicated that they are very satisfied with the quality of the crack sealing installation, while 13 indicated that they were somewhat satisfied. One respondent indicated "not satisfied" but did not elaborate on the reasons for this response.

- Importance of various factors on the performance of crack sealing in Ohio (Question 14): Respondents were asked to rate the importance of 16 factors on the performance of the crack sealing application, rating each factor as "highly significant," "somewhat significant," or "insignificant," and the results are presented in Figure C.11. Factors that were rated as highly significant by the most respondents, in decreasing order, were application temperature of

sealant (for hot applied), presence of moisture on pavement surface, precipitation rate during installation, application equipment, and crack cleaning prior to installation.

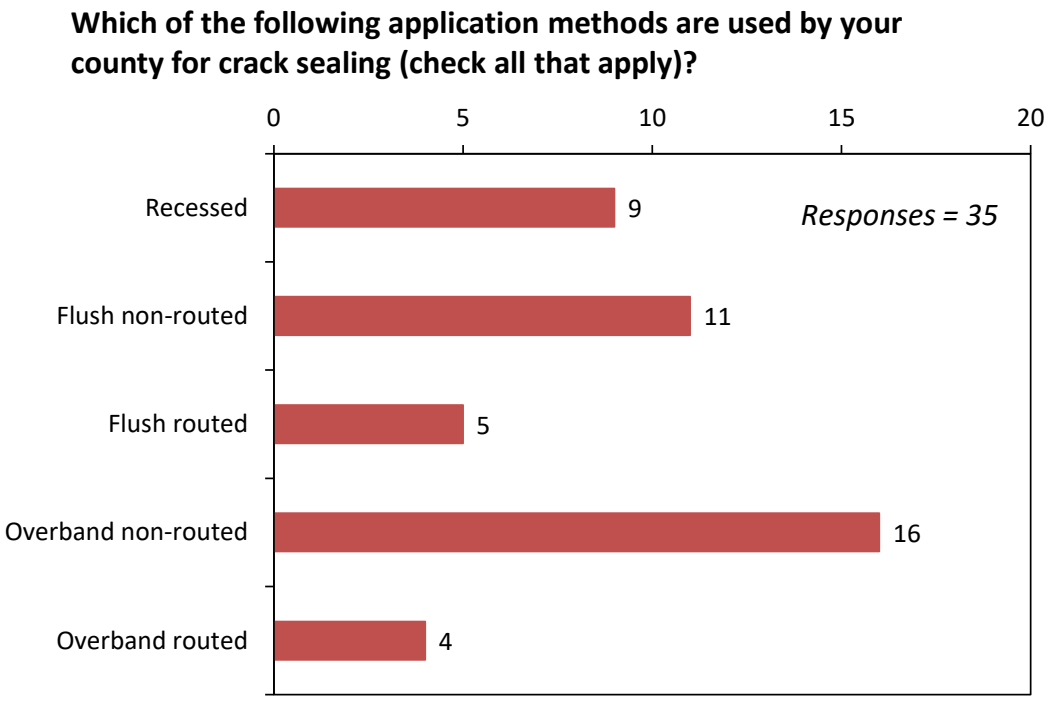

Figure C.9: Application Methods used for Crack Sealing in Ohio.

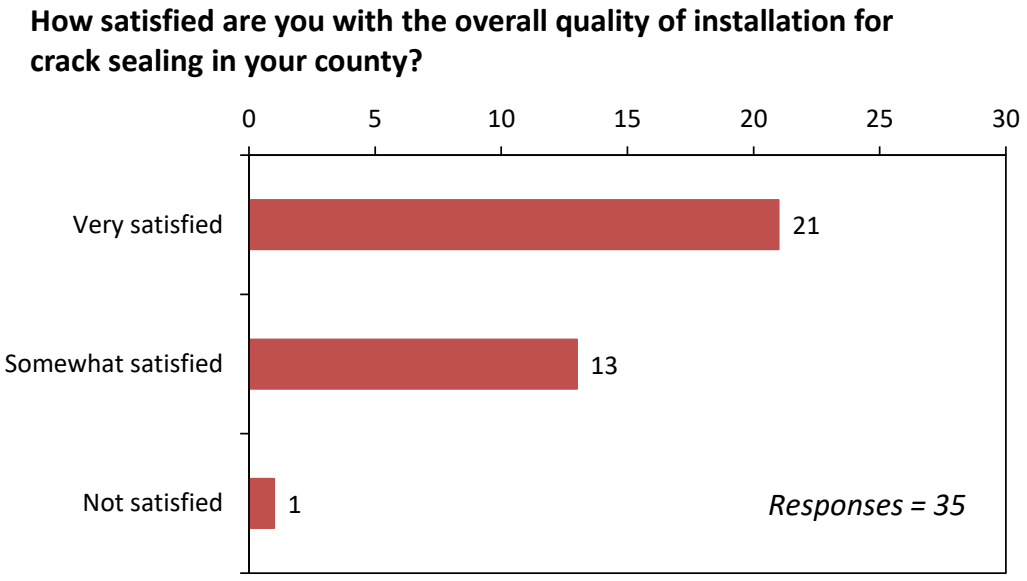

Figure C.10: Satisfaction with Quality of Crack Sealing Installation in Ohio.

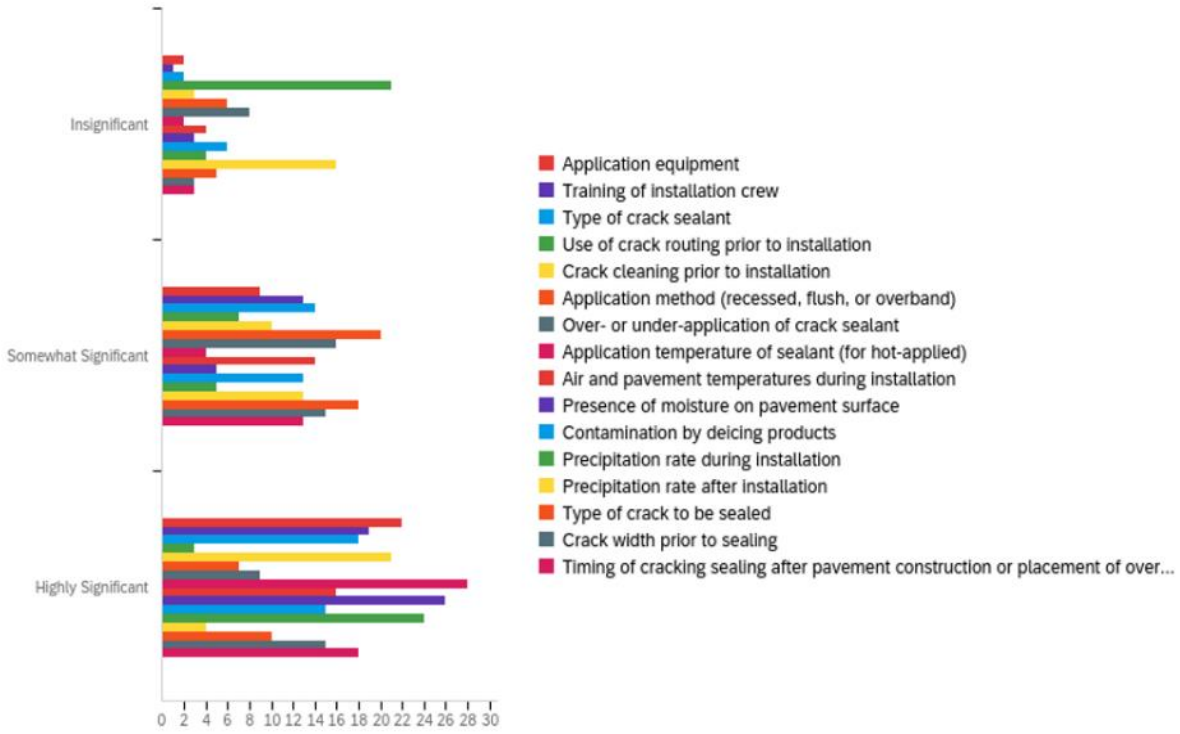

Figure C.11: Importance of Different Factors on Crack Sealing Performance in Ohio.

- Crack sealing distresses commonly encountered in Ohio (check all that apply) (Question 15): The crack sealing distresses reported by respondents are summarized in Figure C.12. The most commonly reported distresses were tracking by vehicle tires, pull out by vehicles, raveling of the crack, adhesive failure/lack of bonding, and spalling of the crack. Cohesive failure was less frequently reported. Other distresses that were reported included "wears off- from traffic driving on it", "snow plows removing it if applied to thick", and "sometimes when the cracks are not deep enough the plow will remove the sealer during snow and ice."

- Typical service life for crack sealing in Ohio (check all that apply) (Question 16): When asked about the typical service life for crack sealing installation in Ohio, the majority of the responses (22 out of 35) indicated two to four years, followed by four to six years (8 responses). Four respondents indicated less than two years, and only one respondent indicated that crack sealing had a service life of more than six years (Figure C.13).

- total of 35 responses were received regarding the effectiveness of crack sealing in extending the service life of pavement surfaces (Figure C.14). The vast majority of respondents indicated either that crack sealing is "very effective (pavement surface life is extended by more than three years)" (15 responses) or is "somewhat effective (pavement surface life is extended by one or two years)" (19 responses). Only one respondent indicated that crack sealing is ineffective.
-

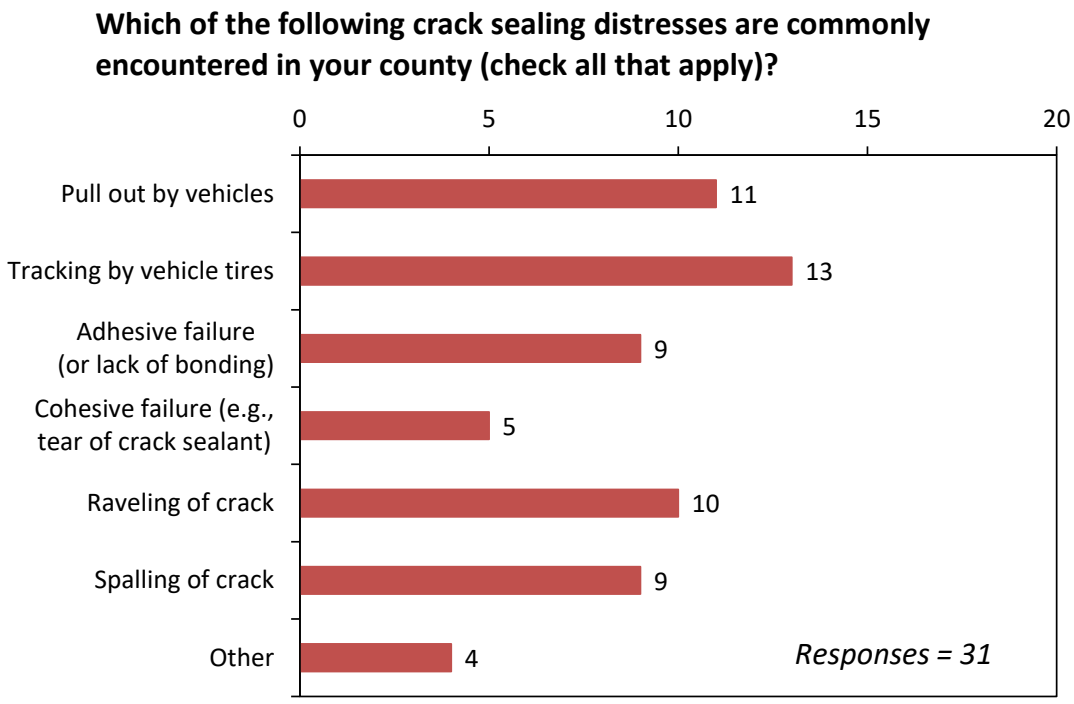

Figure C.12: Crack Sealing Distresses Reported in Ohio.

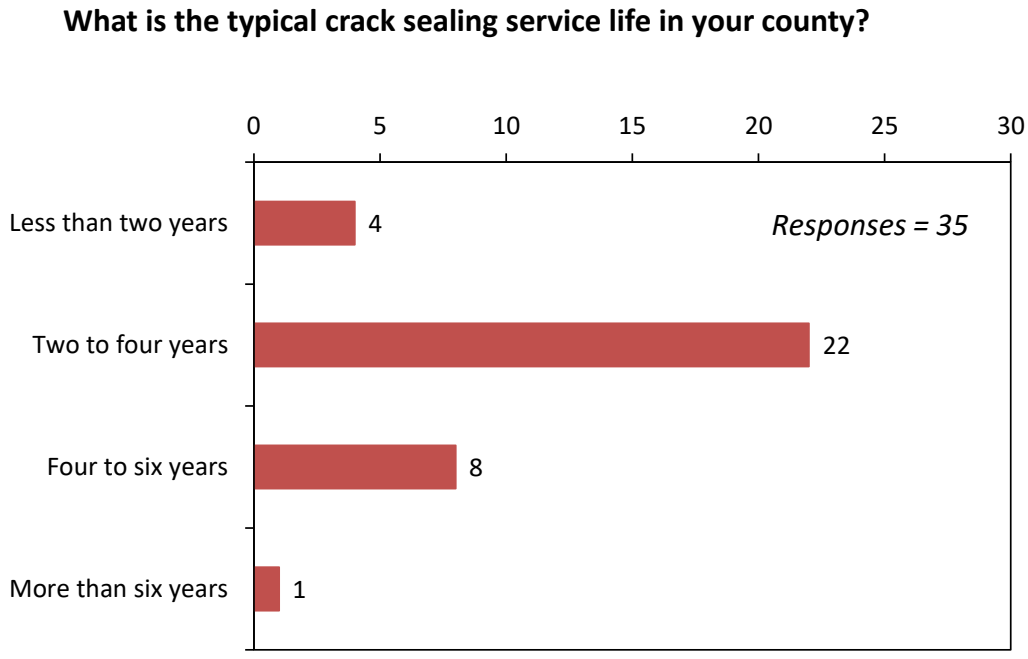

Figure C.13: Typical Service Life of Crack Sealing in Ohio.

- Effectiveness of crack sealing in extending pavement service life in Ohio (Question 17): A

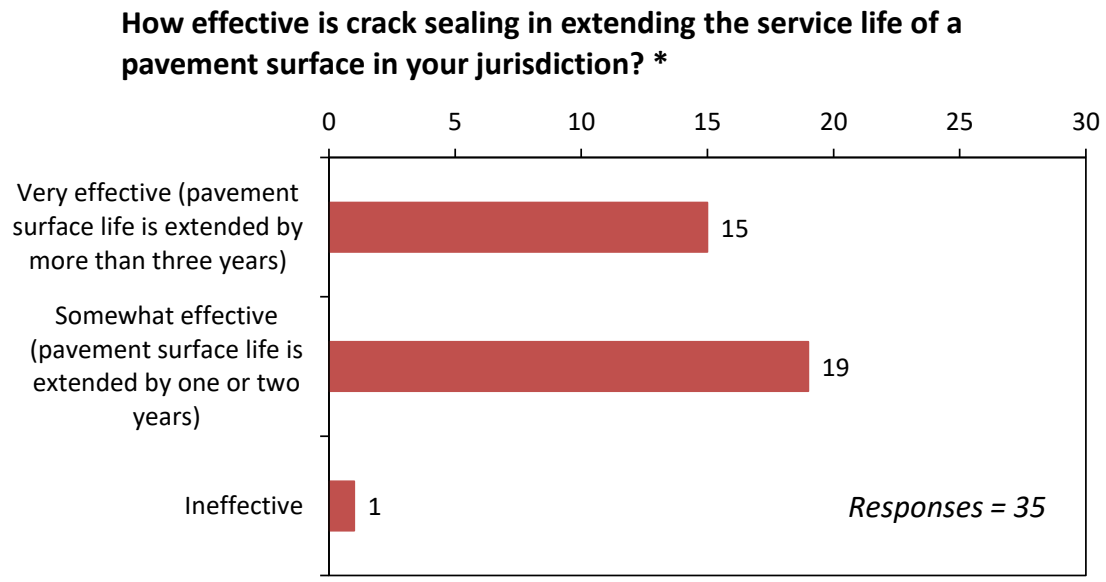

Figure C.14: Effectiveness of Crack Sealing in Ohio.

- Issues encountered during crack sealing in Ohio (Question 18): A total of 35 responses were received for this question. The results are presented in Figure C.15. When asked about the issues encountered when performing crack sealing, the most frequently noted issue was "equipment failure" – this was selected by 28 respondents as well as the one respondent who selected "Other" and indicated that the "crack sealer is very old" and it "breaks down quite often." A total of seven respondents selected "None of the above," indicating that they had observed no adverse effects during crack sealing. Worker injury and damage to other vehicles by the crack sealing crew were each selected by four respondents. Only one respondent reported damage to the crack sealing equipment that was caused by passing traffic.

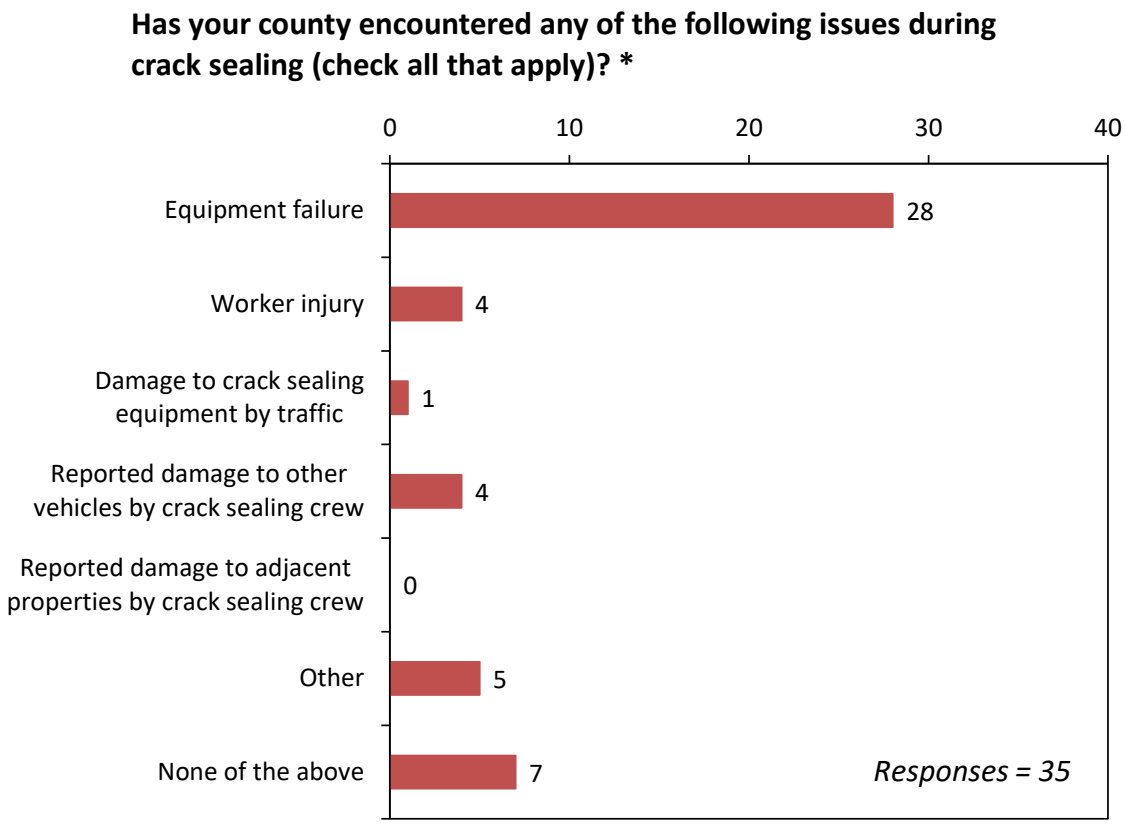

Figure C.15: Issues Encountered during Crack Sealing in Ohio.

- Best practices for crack sealing in Ohio (Question 19): When asked for recommendations for best practices to improve crack sealing, ten of those surveyed provided responses. A summary of these responses is presented in Table C.1.

Table C.1 Recommendations for Best Practices to Improve Crack Sealing Performance in Ohio

General Category	Response
Equipment	- I would rent crack sealers per month, per 3 months or per 6 months. I would purchase their recommended material to use per weather conditions and based on the cracking of the pavement. The renter would be responsible for the maintenance of the machine if it goes down or isn't working properly. - It is tough to get all the crack sealing done when you share equipment. When it is time to do it, the other counties are doing the same thing so either you rent a machine or wait. When renting, weather plays a huge factor in our work. I cannot justify having a rented machine sit doing nothing and not putting any hours on it.
Equipment (Continued)	- Put crack sealing equipment on a cycle or just rent it. Our problem is ALWAYS equipment.
In-house vs. contracting	- Contract this out. Contractor is more efficient.
Pavement distress	- Limiting crack sealing to not being applied to alligatored pavements is a better use of the resource.

Timing of work	- Get on a road early, as soon as cracks develops (usually after third year after new).
Worker safety	- Be sure to cover safe loading of block rubber with your crews and the importance of using the proper PPE. All due to extreme material temperatures.
Cleaning/preparation	- We always blow out cracks whenever we are doing the crack sealing.

- Final thoughts or comments on crack sealing in Ohio (Question 20): When asked for final thoughts or comments to benefit the research project, one respondent suggested the following: "I would look at the cost of ODOT vs. Contractor for crack sealing."

C.2.3 Responses from ODOT districts and counties that no longer perform crack sealing

If a respondent indicated in their response to Question 3 that their agency previously performed crack sealing but no longer does, the survey jumped directly to Question 21.

- Reasons why agencies in Ohio stopped using crack sealing (Question 21): When asked why their agency no longer performs crack sealing, eight respondents elaborated on the reasons. Their responses are summarized in Table C.2. As can be noticed from this table, numerous agencies reported that they did not have enough employees to perform crack sealing and/or have contracted out their crack sealing work.

Table C.2 Reasons Why Some Ohio Counties No Longer Perform Crack Sealing

General Category	Response
Multiple reasons	- Was decided crack sealing would not be one of our core functions. Lack of manpower, slow machine.
In-house vs. contracting	- Contract this out. Contractor is more efficient. - Our crack sealing is done through a district contract. - We have our crack sealing contracted out. - Most of our roads in need of crack sealing are contracted.
Human resources	- Not enough employees. Only crack seal culverts and paving train patches. - Crews did not like to and limited human resources.

D.1 National Survey Responses

A total of 34 responses to the national survey of state transportation agencies were received. The respondents included people with positions such as civil engineer, research engineer/scientist, state engineer, state highway maintenance director, project engineer, pavement preservation engineer, roadway operations manager, asset management engineer, pavements branch manager, pavement preservation/rehabilitation/management engineer, pavement design engineer, materials engineer, director of public works, strategic operations manager, maintenance engineer, road/street superintendent, sewer superintendent, technician/project supervisor, roadside maintenance specialist, or client services manager.

The respondents represented a variety of agencies. Responses were received from state departments of transportation in the following states: Alabama, Alaska, Arizona (2 responses), Arkansas (2 responses), Florida, Indiana (2 responses), Louisiana, Massachusetts, Michigan, Minnesota, Nebraska (2 responses), New Hampshire, North Carolina, Ohio, Rhode Island, Texas, Utah, Vermont, Virginia, Washington, Wyoming. Responses were also received from The District of Columbia (3 responses), a transportation agency of the US military (U.S. Air Force), four local transportation agencies (the Town of South Hadley, Massachusetts; Winn Parish Police Jury,

Louisiana; the Town of Iowa, Louisiana, the City of Huntingburg, Indiana), and a pavement and bridge preservation company in the northeastern US (Indus, Inc., in Boston, Massachusetts).

C.3.1 General Question

The national survey began with one general question to determine whether or not the respondent's agency performs crack sealing. Subsequent questions were asked of respondents who indicated that their agency currently performs crack sealing or had performed crack sealing in the past, and those who indicated that their agencies had never performed crack sealing were directed to the end of the survey and thanked for their time. Below is the question presented in this part of the survey, along with a summary of the responses to this question.

- Does your agency use crack sealing for pavement preservation? (Question 3): A summary of the responses regarding the use of crack sealing for pavement presentation in presented in Figure C.16. In this figure, the y-axis indicates a specific response to the question, while the x-axis indicates the number of respondents who chose the specific response. As can be noticed from this figure, 31 (out of 34) respondents indicated that their agency currently uses crack sealing, one respondent indicated that their agency used crack sealing in the past but no longer uses it, and two respondents indicated that their agency has never used crack sealing. For respondents who indicated that their agency has never used crack sealing, this was the last question on the survey, and the respondents were thanked for their time.

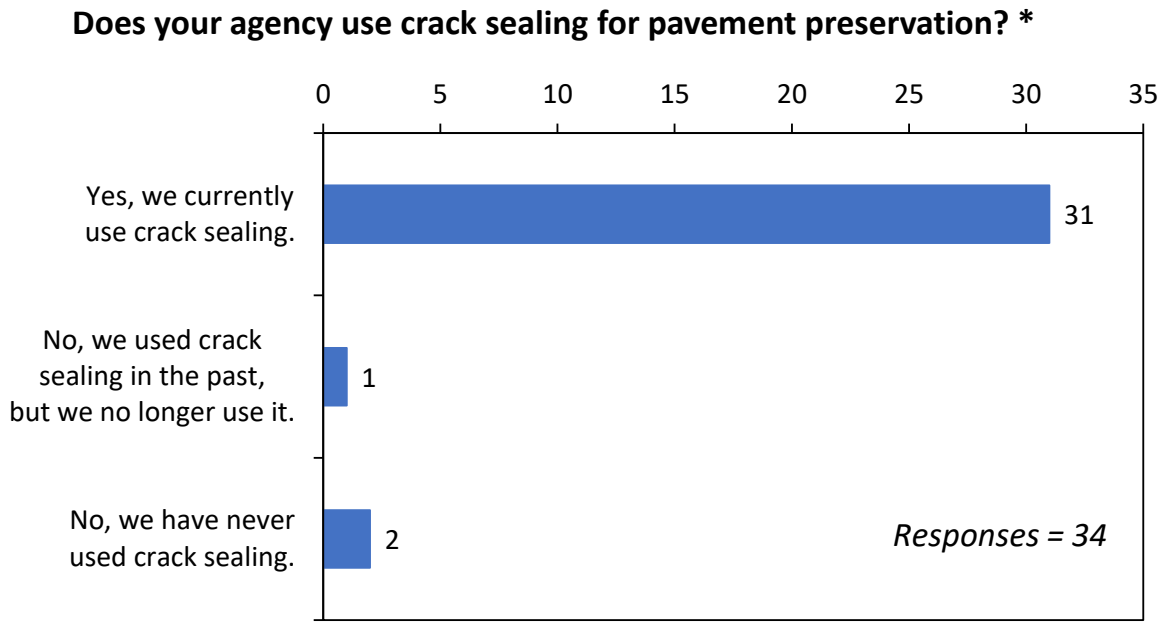

Figure C.16: Use of Crack Sealing for Pavement Preservation in Various States.

C.3.2 Responses from agencies in various states that perform crack sealing

- Crack sealing is performed by (check all that apply) (Question 3): A total of 30 responses were received for this question. The survey results, shown in Figure C.17, reveal that eight respondents reported that crack sealing is performed by an in-house crew, thirteen respondents

reported that crack sealing is performed by an in-house crew or by external contractors, and nine respondents indicated the work is performed by external contractors.

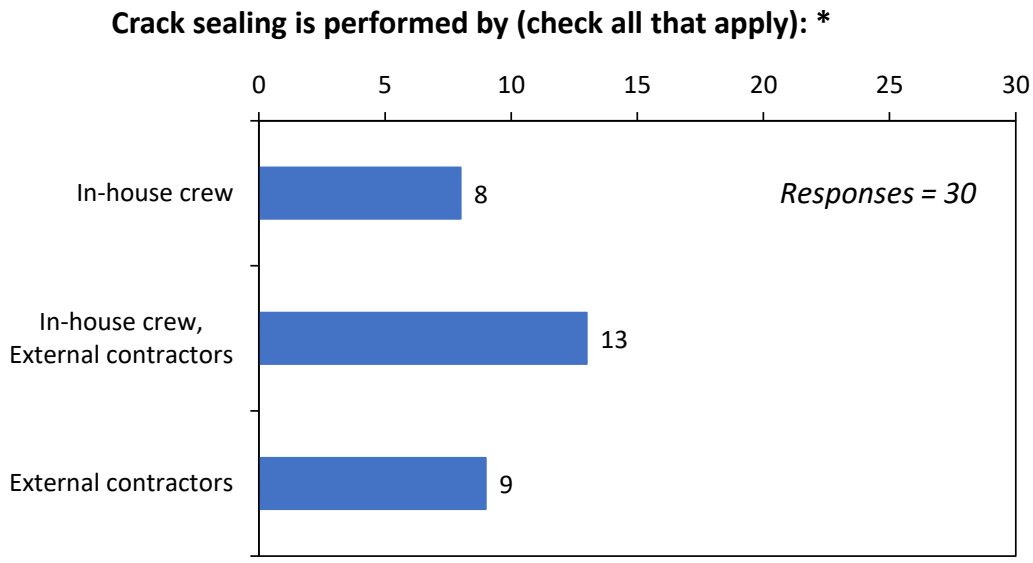

Figure C.17: Percentage of Crack Sealing Performed by In-house Crews and Contractors.

- Criteria used for selecting roads for crack sealing (check all that apply) (Question 5): Similar to the results for the ODOT survey, the results for the national survey (shown in Figure C.18) indicate that the most common criteria are the crack width, the type of crack, and the age since construction. Less common are the type of road, the type of pavement (flexible or rigid), or the traffic level.

- Annual budget for crack sealing (Question 6): Of the 25 individuals who responded when asked about their agency's annual budget for crack sealing (Figure C.19), fifteen indicated that their agency spends more than $500,000, while five indicated that their agency spends more than $150,000 but less than or equal to $500,000. The high percentage of responses in these two categories likely reflects the proportion of respondents from state transportation agencies, which typically have more lane miles of roads under their jurisdiction that are included in their crack sealing program. For the remaining respondents, three representatives reported that their agency spends more than $50,000 but less than or equal to $150,000, and two reported that their agency spends less than or equal to $50,000 per year.

- Crack cleaning and preparation methods (Question 7): A total of 28 responses were received for this question. When asked what crack cleaning and preparation methods have been used by their agency prior to crack sealing, 27 respondents indicated that cracks are cleaned using compressed air (Figure C.20). Other methods reportedly used were routing (16 responses), hot air lance (15 responses), cleaning with a wire brush (3 responses), sawing (3 responses), or cleaning with pressurized water (2 responses). No respondents indicated that they used sand blasting to clean cracks in the road surface prior to sealing them.

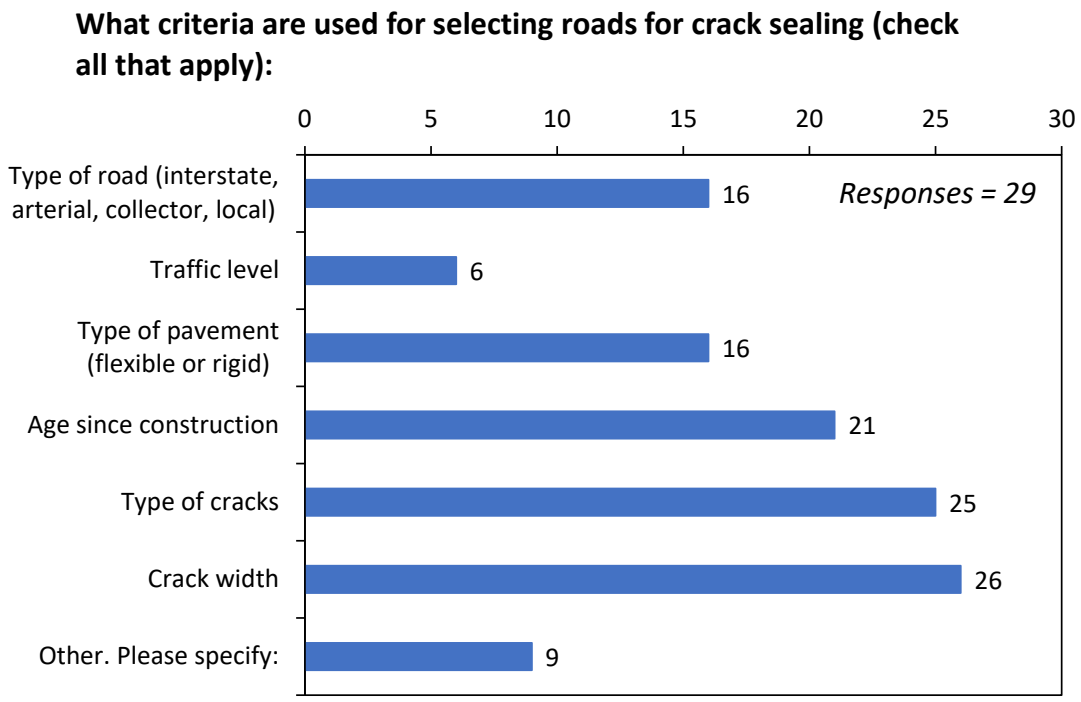

Figure C.18: Criteria Used for Selecting Roads for Crack Sealing.

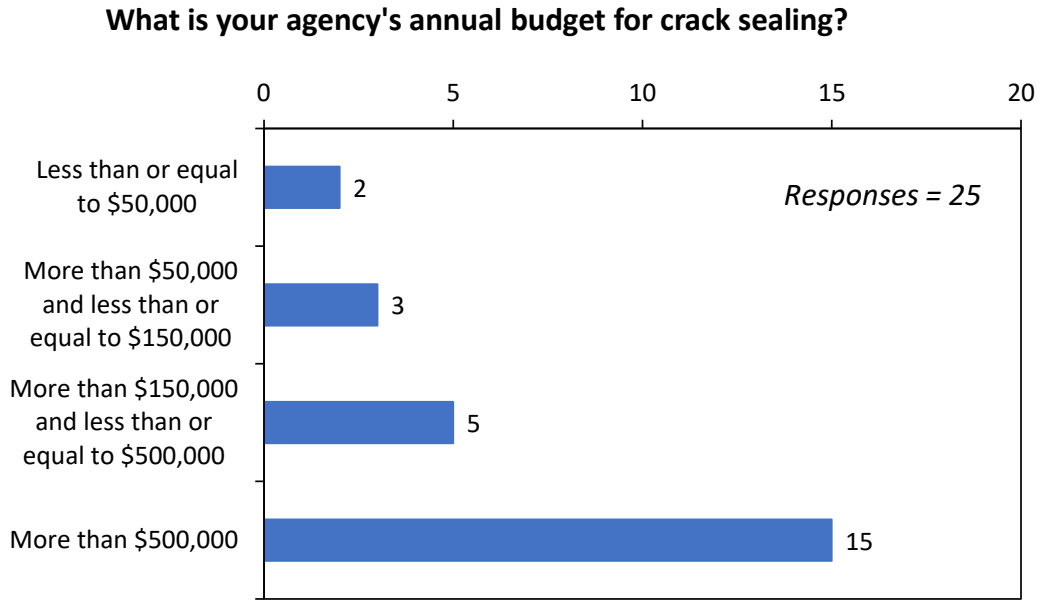

Figure C.19: Annual Budget for Crack Sealing for Various Agencies.

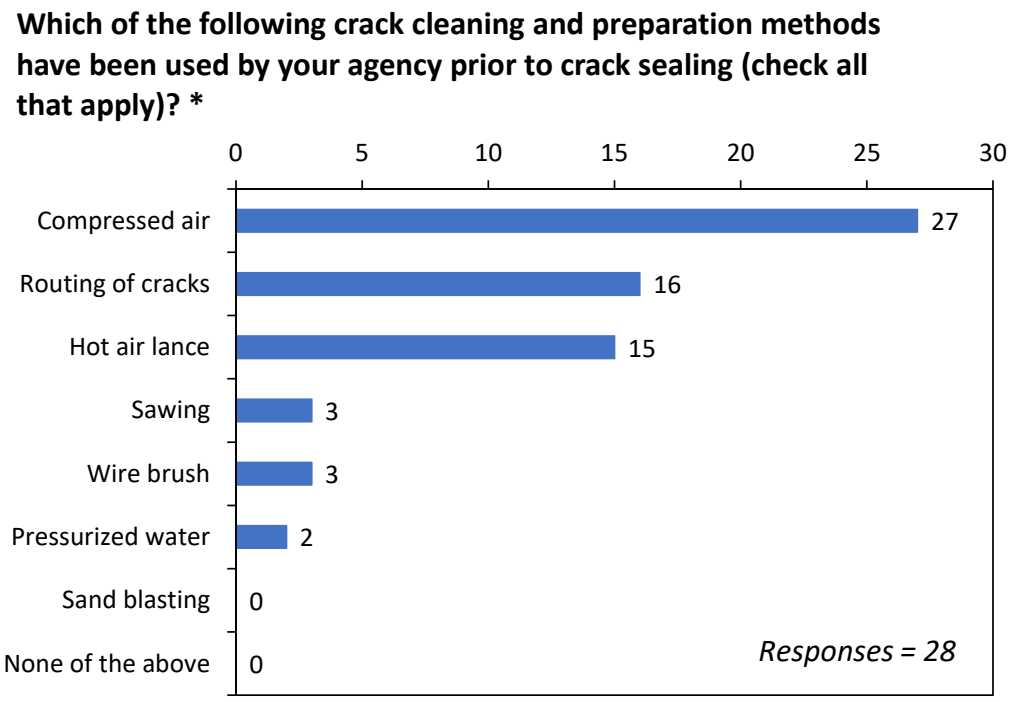

Figure C.20: Crack Cleaning and Preparation Methods used by Various Agencies.

- Type of crack sealing equipment used (Question 8): When asked what crack sealing equipment is used by their agency, the vast majority of the respondents (19 out of 25) indicated that their agency uses tow-behind units (Figure C.21). The manufacturers mentioned for the tow-behind equipment were mainly Crafco, one respondent mentioned Sealmaster, one respondent mentioned Cimline Magma 230, and two respondents were not sure which manufacturer produced the units used by their agency. Nine respondents reported that their agency uses small walk-behind units, but they were not sure which manufacturer(s) produced the equipment. Two respondents indicated that their agency uses automated/robotic equipment. One respondent indicated "We recently had a demo and are considering this technology for the future. Current technology appears to be in need of further development to be deemed a good option. RMV robotic crack sealer: https://rmv.llc/," and the other respondent mentioned "Although not technically crack filling/sealing, we use a Schwarze Spray Patcher - RoadPatcher for pothole repairs and some crack treating." Five respondents indicated that other equipment is used for this purpose; their responses included a kettle, a large self-contained unit with a 1,000-gallon tank and all appurtenances on a single truck, and contractor-built 1,100-gallon trucks.

- Has the agency ever used or experimented with using automated/robotic crack sealing equipment (Question 9): When asked if their agency used or experimented with using automated/robotic crack sealing equipment, 23 of the 25 respondents indicated that their agency has not, while two indicated that their agency has used such equipment (Figure C.22).

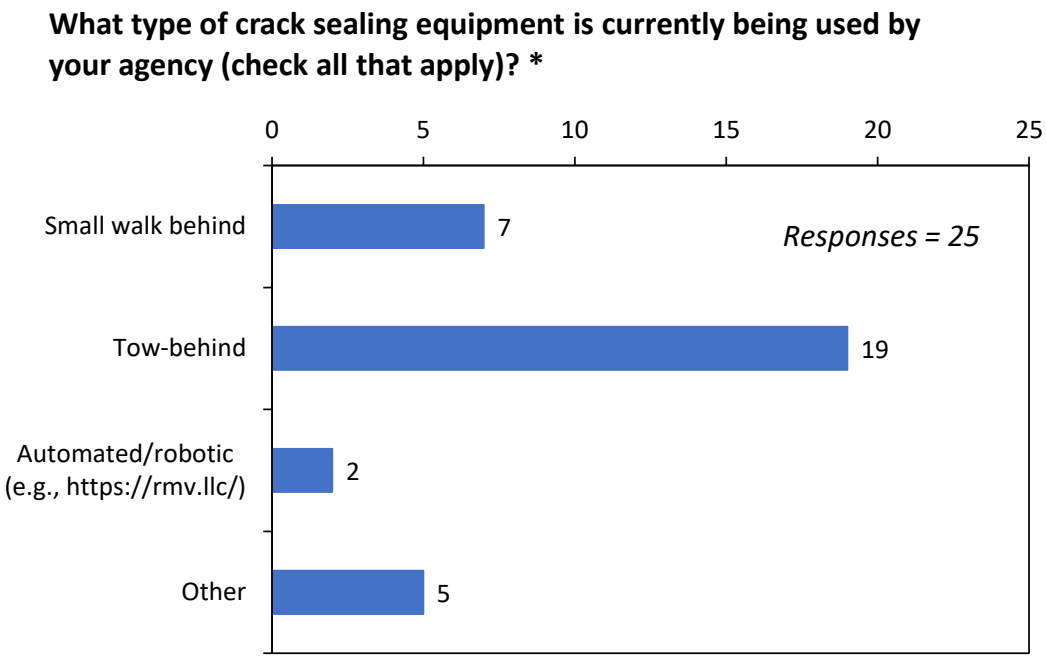

Figure C.21: Crack Sealing Equipment used by Various Agencies.

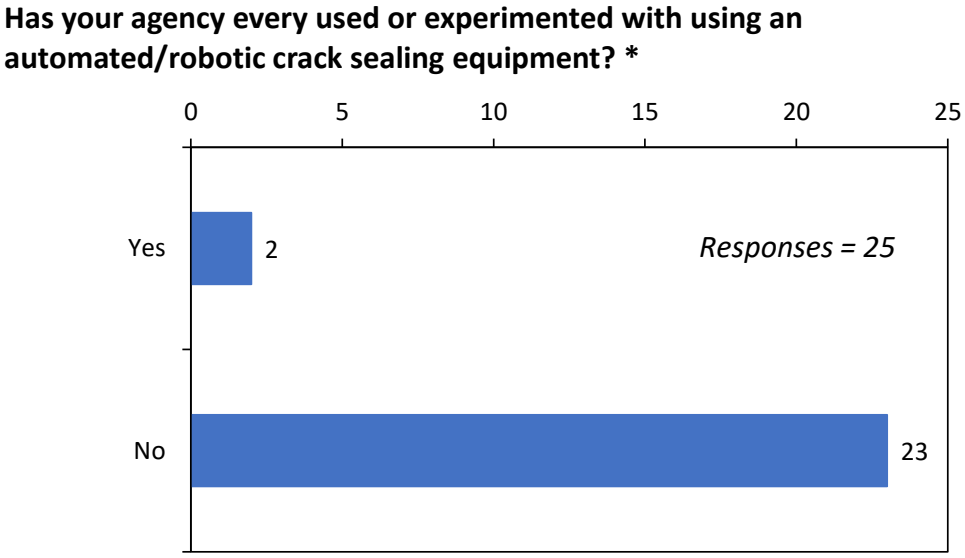

Figure C.22: Use of Automated/Robotic Crack Sealing Equipment by Various Agencies.

- Satisfaction with automated/robotic crack sealing equipment (Question 10): Two individuals responded to the question of how satisfied they are/were with automated/robotic crack sealing equipment (Figure C.23). The two respondents reported being "Not satisfied" with this equipment. When the respondents were asked to elaborate on the reasons for their dissatisfaction, one indicated "Product of robotic sealing would struggle to meet standards for activity (e.g., missed cracks, over application, alignment/calibration issues). Conceptually, the

reduced crew size is a large draw both from reduced manpower and safety benefits." The second indicated, "We have not used but as I commented on the previous question - the automated equipment that I have seen does not perform all of the tasks necessary."

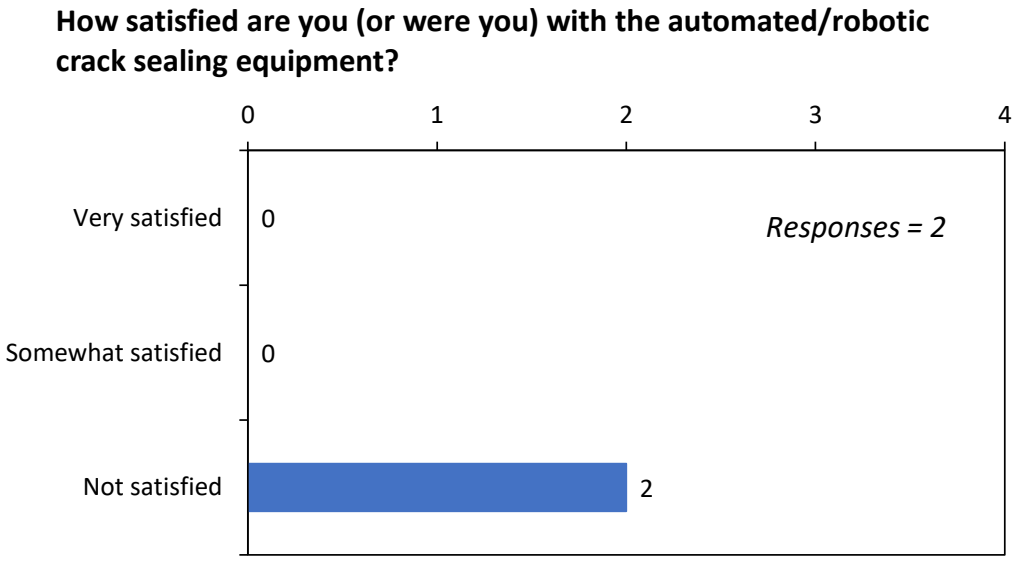

Figure C.23: Satisfaction with Automated/Robotic Crack Sealing Equipment.

- Type of material used for crack sealing (Question 11): All respondents indicated that their agency uses hot-applied crack sealing materials (Figure C.24). One respondent indicated that cold-applied materials are also used. The respondents mentioned a variety of hot-applied materials, including Crafco RoadSaver, SealMaster Cracksaver, and block rubber materials. No information was provided about the type and producer of the cold-applied material.

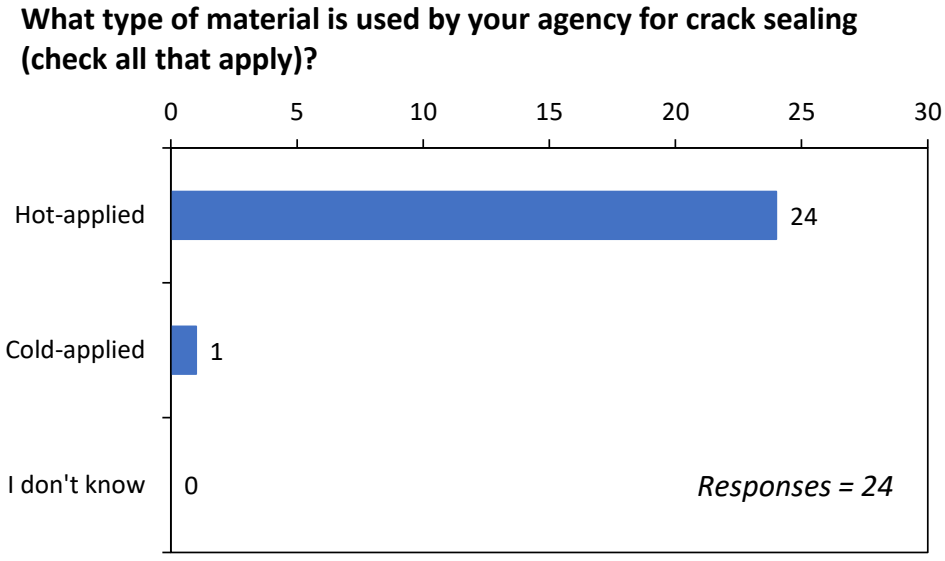

Figure C.24: Type of Material used for Crack Sealing by Various Agencies.

- Application methods used for crack sealing (Question 12): A total of 24 individuals responded to this question. In the responses shown in Figure C.25, the applications are listed along the y-axis, and the number of responses is indicated on the x-axis. The most common response was overband non-routed (17), followed by flush non-routed (10), flush routed (10), overband routed (6), and recessed (5).

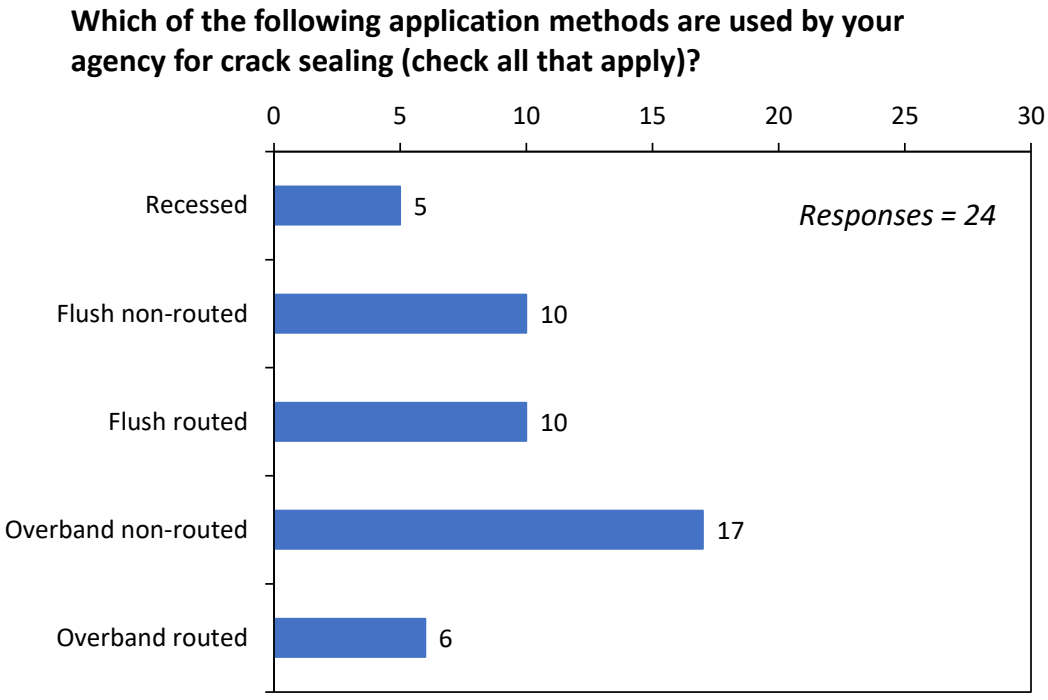

Figure C.25: Application Methods used for Crack Sealing.

- Satisfaction with the overall quality of crack sealing installation (Question 13): A total of 24 individuals responded to this question (Figure C.26). The majority (13) indicated that they are very satisfied with the quality of the crack sealing installation, while nine indicated that they were somewhat satisfied. Two respondents indicated "not satisfied." When these two respondents were asked to elaborate on the reasons for their dissatisfaction, one replied "Very satisfied if it is applied correctly. If it is not applied correctly it tends to come up with tires over it." The other replied "Performance has been varied and primarily an effect of the care taken to perform the work. Placement temperature (ambient and material) are also major contributors to performance."

- Importance of various factors on the performance of crack sealing (Question 14): Respondents were asked to rate the importance of 16 factors on the performance of the crack sealing application, rating each factor as "highly significant," "somewhat significant," or "insignificant," and the results are presented in Figure C.27. Factors that were rated as highly significant by the most respondents, in decreasing order, were "training of installation crew and "crack cleaning prior to installation" (which tied for the most responses), followed by precipitation rate during installation, application temperature of sealant (for hot applied), presence of moisture on pavement surface, and over- or under-application of crack sealant.

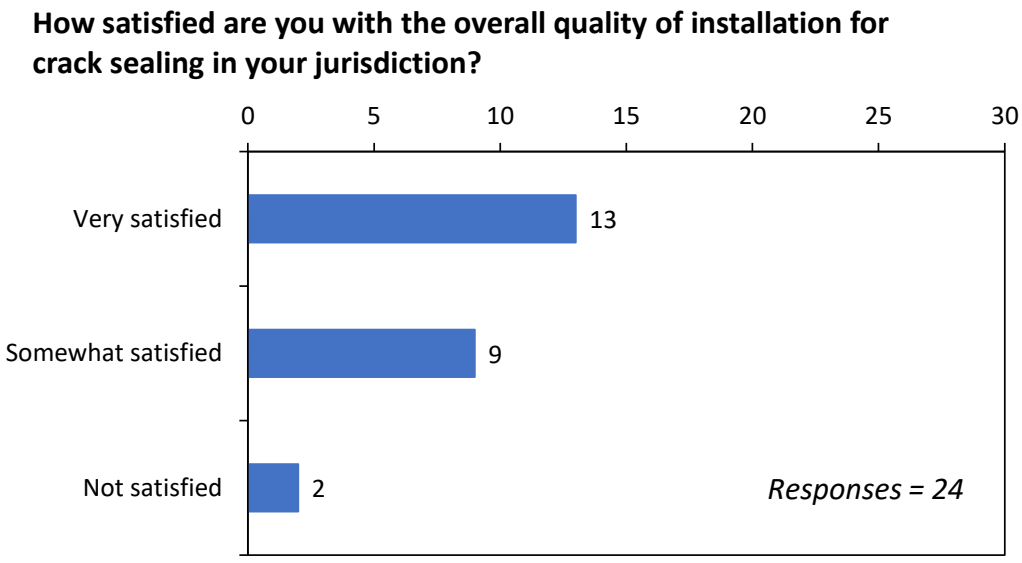

Figure C.26: Satisfaction with Quality of Crack Sealing Installation.

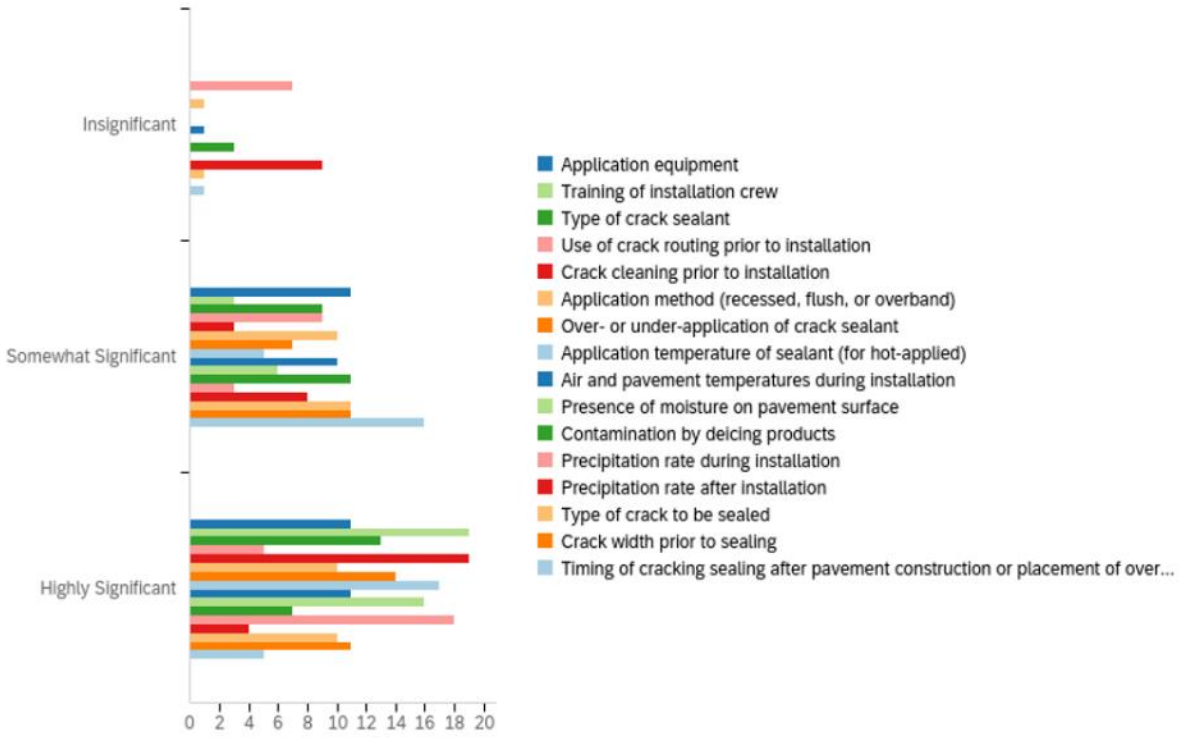

Figure C.27: Importance of Different Factors on Crack Sealing Performance.

- Crack sealing distresses commonly encountered (check all that apply) (Question 15): A total of 21 individuals responded to the question on crack sealing distresses. The distresses reported by respondents and the frequency of each distress are summarized in Figure C.28. The most

commonly reported distresses were adhesive failure/lack of bonding (11), spalling of the crack (7), pull out by vehicles (6), and raveling of the crack (5). Tracking by vehicle tires (4) and cohesive failure (4) were less frequently reported. Other distresses (6) that were reported included alligator cracking where the pavement starts to pull apart (usually soft spots under the pavement) and damage/ripping of crack seal by plows if cracks are overfilled (more common on airport runways due to frequency of plowing and snow/ice removal). Another respondent who chose "other" indicated that if the crack sealing is installed with the proper material and workmanship along with the application of Crafco DETACK sealant finisher, the failure rate is extremely low. One respondent indicated that their agency has observed all the types of distresses included on the list in this survey question, but adhesive failure was the most commonly encountered distress. Another indicated that they used to have problems with cracks that were routed before they were sealed.

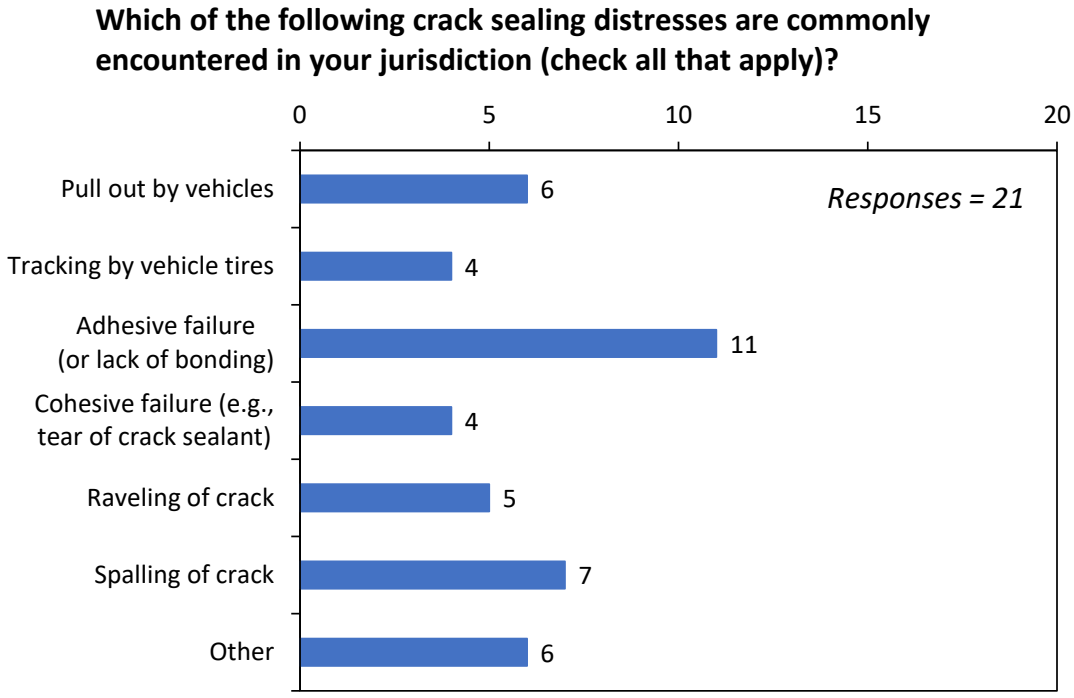

Figure C.28: Crack Sealing Distresses Reported.

- Typical service life for crack sealing (check all that apply) (Question 16): When asked about the typical service life for crack sealing installation, 21 responses were received (Figure C.29). The majority of responses (13) indicated two to four years, followed by four to six years (6). Two respondents indicated that crack sealing had a service life of more than six years. No respondents indicated a service life of less than two years.

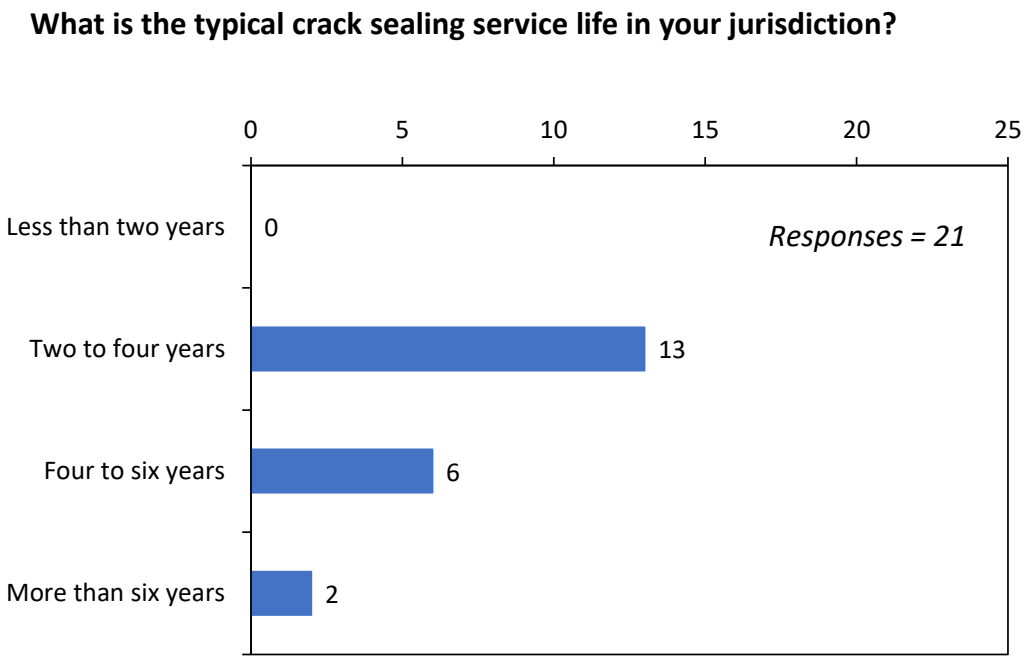

Figure C.29: Typical Service Life of Crack Sealing.

- Effectiveness of crack sealing in extending pavement service life (Question 17): A total of 24 responses were received regarding the effectiveness of crack sealing in extending the service life of pavement surfaces (Figure C.30). The majority of respondents indicated either that crack sealing is "very effective (pavement surface life is extended by more than three years)" (17) or is "somewhat effective (pavement surface life is extended by one or two years)" (7). No respondents indicated that crack sealing is ineffective.

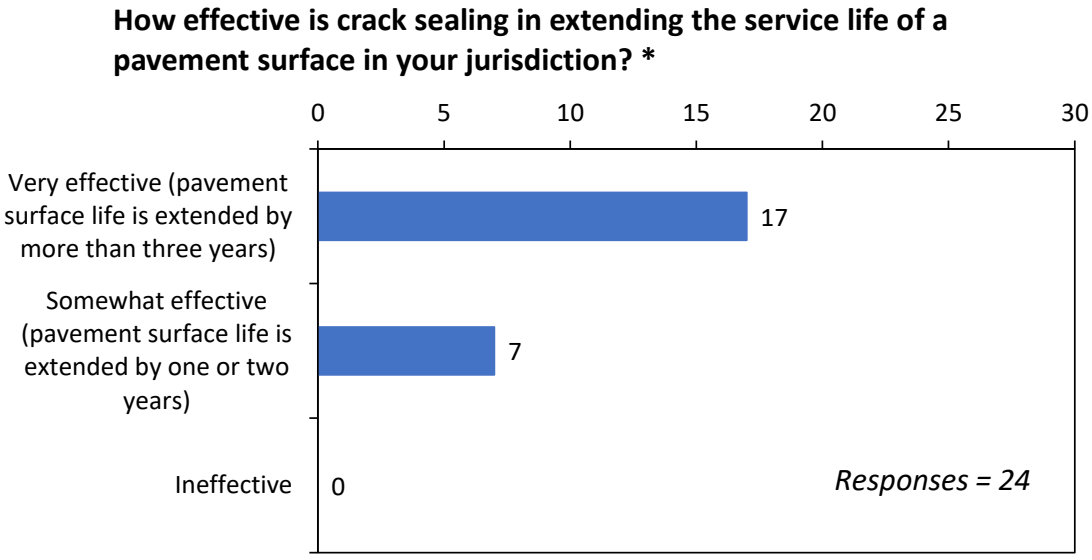

Figure C.30: Effectiveness of Crack Sealing.

- Issues encountered during crack sealing (Question 18): A total of 21 individuals responded to this question (Figure C.31). When asked about the issues encountered when performing crack sealing, the most frequently noted issue was "equipment failure" – this was selected by 13 respondents, followed by "worker injury" and "damage to other vehicles by the crack sealing crew," which were each selected by six respondents. Four respondents reported damage to the crack sealing equipment that was caused by passing traffic. Four respondents selected "Other", and one noted that extreme caution is required while blowing out the cracks to prevent damage to surrounding vehicles and injury to nearby pedestrians. The remaining five respondents selected "None of the above."

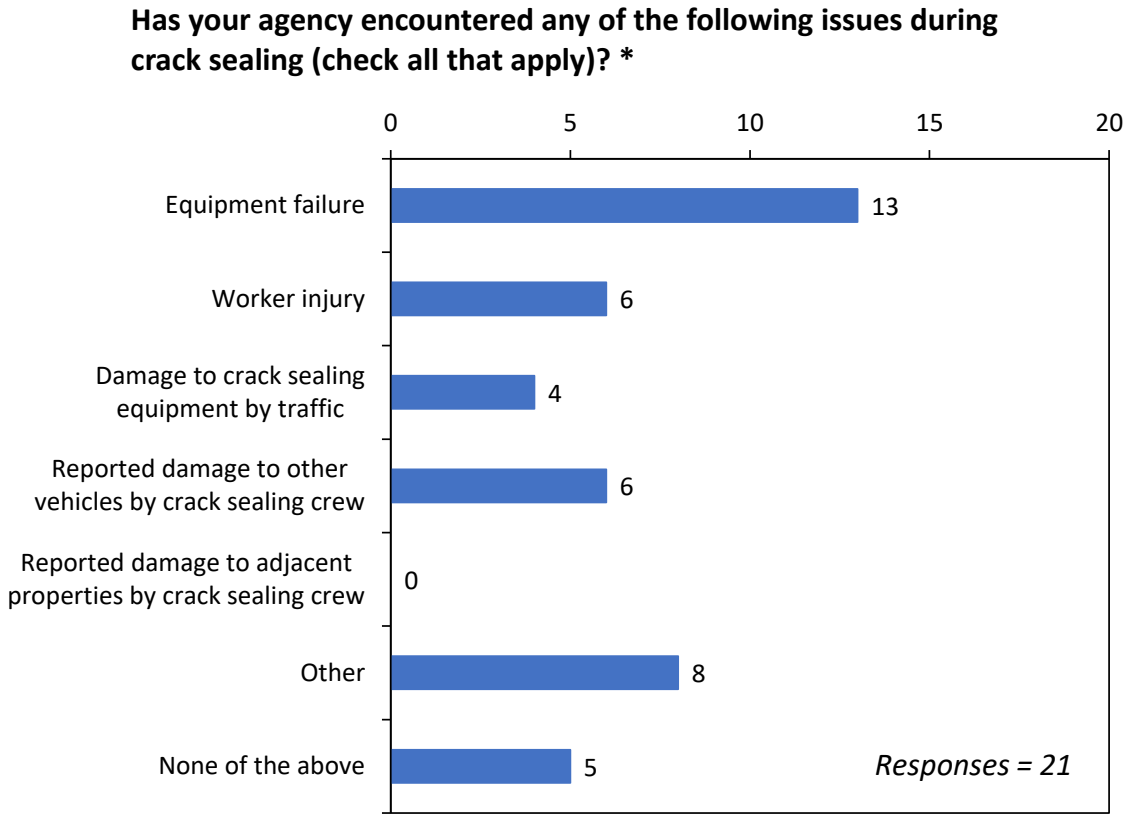

Figure C.31: Issues Encountered during Crack Sealing.

- Best practices for crack sealing (Question 19): When asked for recommendations for best practices to improve crack sealing, ten of those surveyed provided responses. A summary of these responses is presented in Table C.4. As can be noticed from this table, numerous suggestions were received from the respondents in terms of materials, equipment, installation, ambient conditions, observed distresses, timing of the work, worker training, and cleaning/preparation.

Table C.4 Recommendations for Best Practices to Improve Crack Sealing Performance

General Category	Response
Materials	- ASTM 6690 rubber material is good in areas with high foot traffic (parking lots) and less plowing as plows tend to pull out the "rubber snakes" many used to see along roadways prior to the newer engineered materials. A fiber reinforced material with polymer and a smaller quantity of rubber has proven to be the best fit for the Northeast.
Materials (Continued)	- We only use PCRM for product now as it has given us the best performance for the cost and has shown to improve our roads. - ARDOT primarily uses hot applied crack sealant of various types to seal cracks in asphalt pavements and the joint between asphalt shoulders to concrete roadways. - Use a hot sealant, preferably one that's modified and PG graded. - Equally important is choosing the proper material for the crack type. Early treatment in pavement life is the best approach to cost-effective pavement life extension.
Equipment	- When crack filling or sealing in cooler temperatures (< 50°F), a heat lance is recommended to dry and heat cracks before filling. Most suppliers require an application temperature ≥ 40°F for applying their materials. Care must be exercised when using the heat lance to prevent scorching or burning the pavement. - Equipment is maintained periodically and air lance ratings checked for temp and air pressure.
Installation	- Non-routed overband has been highly successful for a majority of cracks as long as the surface is clean and dry. It provides much quicker installation and significantly more cost effective over routing. There are some recent NCAT & NCHRP studies showing the life of crack sealant is very dependent on the age of the pavement -- much better performance if crack sealing is done while the pavement is still in good condition. - Carefully plan when crack seal is being used in relation to AST or other paving to prevent blistering. - Good clear specs with Safety and QA provisions (Enforce MUTCD). - Enforce QA provisions and conduct testing as soon as possible to keep up with production. - Ensure blotting material is applied immediately - to avoid a mess created by ensuing traffic.
Ambient conditions	- Biggest thing is no moisture on pavement surface. Also, you don't want the pavement surface to be too hot or the crack seal won't cure/dry very quickly and you have to keep the lane closed to traffic for longer and risk pull up by vehicles. - Weather limitations should be strictly enforced (No sealing when cold or chance of precipitation in Weather forecast.
Pavement distress	- If the roadway is extensively cracked make sure another pavement preservation treatment is not more cost effective (chip seal, scrub seal, cape seal, etc.)
Timing of Work	- Apply at the proper time to prevent underbanding or overbanding when pavement contracts or expands.
Worker training/safety	- Train your application staff to apply sealant within guidelines (to include selection of candidate pavement/roads to undergo preservation treatment).

Worker training/safety (Continued)	- The most important part of this process has been training. A well-established SOP and the verification though QC\QA check has been vital to success. - Like many strategic maintenance treatments used to preserve pavement, crack sealing performance is primarily influenced by knowledge of installation crew and care when installing. - Used trained field crews and trained state inspectors.
Cleaning/preparation	- Making sure the joint is clean and dry prior to placement of joint sealant is very important. - A clean and dry crack is key for good performance. These conditions are needed for good adherence of the crack sealing material to the sidewalls of the crack. If there is water in the crack, delay sealing until excess moisture is gone. Crack treatments perform best when these conditions are met. - Prep, prep & more prep. Cracks need to be clean and dry.

- Final thoughts or comments on crack sealing (Question 20): When asked for final thoughts or comments to benefit the research project, one respondent indicated that routing was not found to be effective on aged pavements as additional microcracks are formed that ultimately erode/destabilize the routed and sealed cracks, creating pullouts and other distresses.

C.3.3 Responses from other states that no longer perform crack sealing

If a respondent indicated in their response to Question 3 that their agency previously performed crack sealing but no longer does, the survey jumped directly to Question 21.

- Reasons why agencies stopped using crack sealing (Question 21): When asked why their agency no longer performs crack sealing, one respondent elaborated on the reason: "We had to hire contractors and it was too expensive."