Connecting South Dakota and the Nation
South Dakota
Department of Transportation
Office of Research

SD2016-03-F

Performance of Asphalt Concrete Crack Sealants in South Dakota

SD2016-03
Final Report

Prepared by:
Damon Fick
Western Transportation Institute
Montana State University

Bozeman, MT 59717 **October 31, 2020**

DISCLAIMER

The contents of this report, funded in part through grant(s) from the Federal Highway Administration, reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views of policies of the South Dakota Department of Transportation, the State Transportation Commission, or the Federal highway Administration. This report does not constitute a standard, specification or regulation.

ACKNOWLEDGEMENTS

This work was performed under the supervision of the SD 2016-3 Technical Panel:

Dave Huft.. Research Program Manager
Thad Bauer.. Research Administration
Dan Vockrodt.. Engineering Manager, Pierre Area
Rick Rowen.. Materials Engineer
Nate Van Den Oever.. Research Engineer, Office of Research
Micah Howard .... Research Engineer, Office of Research
Jerry Schaefer... Materials Engineer, Certification & Accreditation
Brian Vandam .... Transportation Project Manager, Sioux Falls Area
Chad Hintz .... Lead Highway Maintenance Worker, Mobridge Area
Gregg Ulmer .... Highway Maintenance Supervisor, Winner Area
Toby Crow .... Executive Vice President, South Dakota Association of General Contractors
Ken Swedeen .... Executive Director, Dakota Asphalt Pavement Association

The contribution of the following is gratefully acknowledged:

Jordan Brown .... Project Engineer, Watertown Area
BrianWenisch.. Transportation Specialist, Yankton Area

This work was performed in cooperation with the United States Department of Transportation Federal Highway Administration.

TECHNICAL REPORT TITLE PAGE

<table>
<tr><td>1. Report No.
SD2016-03-F</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">**4. Title and Subtitle**
Performance of Asphalt Concrete Crack Sealants in South Dakota</td><td colspan="2">**5. Report Date**
October 31, 2020</td></tr>
<tr><td colspan="2">6. Performing Organization Code
Enter any/all unique numbers assigned to the performing organization, if applicable.</td></tr>
<tr><td colspan="2">7. Author(s)
Damon Fick, Ph.D., PE</td><td colspan="2">8. Performing Organization Report No.</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Western Transportation Institute
Montana State University
205 Cobleigh Hall
Bozeman, MT 59717</td><td colspan="2">10. Work Unit No.</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
MSU Project Number 4W6436</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
South Dakota Department of Transportation
Office of Research
700 E. Broadway Ave.
Pierre, SD 57501</td><td colspan="2">13. Type of Report and Period Covered
Final Report, November 2016 - September 2020</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code</td></tr>
<tr><td colspan="4">15. Supplementary Notes</td></tr>
<tr><td colspan="4">16. Abstract
The ingress of surface water and snowmelt through cracks in asphalt pavements may reduce their service life due to wetting of sensitive subsoils or expansion during winter months. Asphalt crack sealants are a relatively low-cost pavement maintenance treatment that helps preserve the integrity of the road surface. The objectives of this research were to; 1) Evaluate eight different ASTM D6690 Type IV crack sealants at two different test sites in South Dakota, 2) Review South Dakota's Standard Specifications for installing asphalt crack sealant materials, and 3) Assess South Dakota's process to select suitable materials for their Approved Product List. A crack sealant index was used to assess the performance of the eight sealants at the two test sites. Results of the evaluation attributed a measured pavement contraction of 21% at one site with generally better performing crack sealants compared with 47% contraction measured at the second site. The reduced pavement contraction was likely a combination of milder winter temperatures and more consistent transverse crack spacing reflected through the concrete pavement beneath the bituminous overlay at this site. Sealant temperatures measured during installation and subsequent laboratory material tests were not consistent indicators of sealant performance and could not be used to identify the variation in performance of the same material at the two locations. South Dakota's installation specifications and process for establishing approved materials was similar to State departments of transportation with similar climates. Recommendations include future evaluations of wider (1 in. or 1.25 in.) routed reservoir widths and delayed chip-sealing activities to determine if additional improvements to South Dakota's crack sealing maintenance can be achieved.</td></tr>
<tr><td colspan="2">17. Key Words
asphalt crack sealant, crack sealant performance, sealant distress, sealant evaluation, crack sealant index</td><td colspan="2">18. Distribution Statement
No restrictions. This document is available to the public from the sponsoring agency.</td></tr>
<tr><td>19. Security Classification (of this report)
Unclassified</td><td>20. Security Classification. (of this page)
Unclassified</td><td>21. No. of Pages
203</td><td>22. Price</td></tr>
</table>

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

TABLE OF ACRONYMS

Acronym	Definition
AASHTO	American Association of State Highway and Transportation Officials
A/CF	Adhesion/cohesion failures
AF	Adhesion failure
APL	Approved Products List
ASTM	American Society for Testing and Materials
BC	British Columbia
BBR	Beam Bending Rheometer
CDOT	Colorado Department of Transportation
CSI	Crack Sealant Index
DTT	Direct Tension Test
DSR	Dynamic Shear Rheometer
FHWA	Federal Highway Administration
HMA	Hot-Mixed Asphalt
IRI	International Roughness Index
MDT	Montana Department of Transportation
MC	Minor cracking
MnDOT	Minnesota Department of Transportation
MTI	Mountain Transportation Institute
NCHRP	National Cooperative Highway Research Program
ND	No distress
NTPEP	National Transportation Product Evaluation Program
NDOR	Nebraska Department of Roads
NHDOT	New Hampshire Department of Transportation
NYDOT	New York Department of Transportation
SDDOT	South Dakota Department of Transportation
OPSS	Ontario Provincial Standards
PCR	Pavement Condition Rating
SC	Secondary cracking
SHRP	Strategic Highway Research Program
WYDOT	Wyoming Department of Transportation

1.0 EXECUTIVE SUMMARY

Transverse cracking in asphalt pavements occurs because of expansion and contraction caused by daily or seasonal temperature variations. The ingress of surface water and snowmelt through these cracks may reduce pavement service life due to wetting of sensitive subsoils or expansion during winter months. Poor performing crack sealants can lead to further deterioration of the cracks over time. In states like South Dakota, where underlying subgrade soils are often poor, water ingress can lower shear strength and/or cause these soils to swell putting increased stress in the cracked area. Crack sealing and filling operations are part of accepted pavement maintenance programs to help preserve the integrity of the road surface and maintain the life of the pavement.

The objectives of this research were to; 1) Evaluate ASTM D6690 Type IV crack sealants on the SDDOT Approved Products List and promising new crack sealants for their suitability for use in South Dakota, 2) Review the South Dakota Standard Specifications for Roads and Bridges for installing asphalt crack sealants, and 3) Review and recommend changes to SDDOT's Approved Product List procedures for selecting suitable asphalt sealant materials. The objectives were accomplished through the following tasks, summarized from the chapters of this report.

1.1 Literature Review

Previous research on the effectiveness and best methods of crack sealing along with specifications from other states with a similar climate to the Upper Great Plains region was examined. The literature review indicates hot-pour materials with high elastic properties at low temperatures remain effective for approximately 3 to 5 years. Although there were mixed results regarding the benefit of crack sealing on the life of the pavement, benefits are more pronounced in areas with sensitive subsoils. Pavement life extensions of up to approximately 2 years have been observed.

1.2 Interviews

Telephone interviews were made with nine individuals, eight of which worked for SDDOT, and one contractor. Crack-sealing experience ranged from 8 to 18 years for those interviewed, all of which acknowledged differences in how Regions manage crack sealing maintenance and most agreeing that current approved products list (APL) is important. There was also a general impression that the lab tests used are not a good indicator of product performance. Several challenges associated with crack sealing in South Dakota discussed during the interviews included:

- Discrepancies between various regions around South Dakota on how sealant failures are characterized.
- Difficulties in evaluating sealants after chip seals are installed.
- Assessing the compatibility between certain types of stone (e.g., quartzite vs. granite) and crack sealant.
- Inconsistencies with sealant variables that contribute to better performance.

1.3 Evaluation of Past Field Performance

Crack sealants on SD Highways 11, 13, 17, 38, 44 and 81 were performing poorly based on a review in 2013 and 2014 by the SDDOT. Many of these sealants were installed only six months prior to these inspections. Similar assessments were made during a visit by the Principal Investigator in 2016. The majority of sealant distress were adhesion failures with surficial cracking of the sealant and intermittent secondary cracking.

1.4 Crack Sealant Installation

Eight different crack sealants were installed at two test sites located on US highway 14, beginning approximately 2 miles west of Highmore and on SD Hwy 50, approximately 3 miles west of Yankton, SD. The test sites were broken into eight sections, each with a different crack sealant material installed. The same contractor performed all crack routing, cleaning, and sealant installations for both the Highmore and Yankton sites on 9/6/2017 and 9/7/2017. Construction information collected during the sealant installation included environmental conditions, pavement conditions, and the overall crack sealing process, in addition to sealant samples for laboratory testing.

1.5 Field Performance Evaluation

The performance of eight crack sealants at the two sites was evaluated during two winter inspections, where pavement contractions were highest and sealant distress was most visible. Eighty-four feet of crack length was observed and documented for each sealant, during each site visit. The sealant performance within this crack length was used to develop a crack sealant index that subtracted a weighted percentage of crack length with observed cracking or adhesion failures from the percentage of crack length with little or no distress conditions. The relative performance of the eight crack sealants as evaluated by the crack sealant index (CSI) are shown below.

Highmore	CSI	Yankton	CSI
Roadsaver 522	**1.3**	**3405M**	**1.6**
Deery 101SD	**0.3**	MacSeal 6690	0.9
Mod 4 3405	**0.1**	**Mod 4 3405**	**0.6**
3405 M	**0.1**	Elastoflex 72	0.6
MacSeal 6690	**0**	**Roadsaver 522**	**0.5**
Deery 101ELT	**-0.1**	**Deery 101SD**	**0.4**
Roadsaver 231SD	**-0.2**	Roadsaver 231SD	0.1
Elastoflex 72	**-0.3**	**Deery 101ELT**	**-0.2**

Chip sealing maintenance at the Yankton site covered only the 12ft lane width, leaving the shoulder crack sealant uncovered. Photographs of the shoulder crack sealants revealed a more uniformly distributed sealant extension over the routed reservoir width compared with concentrated extensions showing signs of distress at the reservoir edges in the chip-sealed sealants.

1.6 SDDOT Standard Specifications for Asphalt Crack Sealants

Standard specifications for State departments of transportation bordering South Dakota were reviewed to identify the current state of practice for asphalt crack sealing operations. Iowa, Nebraska, Minnesota, North Dakota, Wyoming, and Montana, were selected because of their proximity to South Dakota and overlapping climate conditions. The specifications were found to be similar for routing, cleaning, sealing, and temperature restrictions with a few exceptions. One exception is a joint reservoir width of 1.5 in. used by Montana compared with a maximum width of ¾ in. for South Dakota and Minnesota, and ½ in. widths for the other states. Wider joint widths have been shown to improve bond and material extensions at low temperatures by researchers in Canada. South Dakota and Montana are the only two states that include a maximum ambient humidity specification for sealant installations to improve the sealant bond with the pavement.

1.7 SDDOT Approved Products List

South Dakota's evaluation process to include new materials to the Approved Products List (APL) is clearly summarized in a flowchart and includes efficient pathways for adding materials to the APL with a demonstrated history of performance. For newer materials, with less performance data, steps are included for requesting more information from the manufacturer with additional levels of review. South Dakota's evaluation request form for adding materials to their APL does not specifically require sealant manufacturers to list other State departments of transportation that include their product on an approved or qualified product list. Adding this request would clarify if a product has been approved, or is currently only being tested. South Dakota's current APL also doesn't include language similar to Minnesota and Montana that requires a product to be reapproved if changes are made to a material formulation. This addition could clarify the differences between the sealant Deery 101 and Roadsaver 231 which are currently on SDDOT's APL with the products Deery 101ELT, Deery 101SD, and Roadsaver 231SD which were evaluated as part of this investigation.

1.8 Implementation recommendations

1.8.1 Addition of crack sealant materials to South Dakota's APL.

The relatively high performing crack sealants identified in this research should be reviewed and added to South Dakota's approved product list. Viable sealants for future crack sealing maintenance operations are shown below. The shaded sealants are currently included on South Dakota's APL.

Highmore	CSI	Yankton	CSI
Roadsaver 522	1.3	3405M	1.6
Deery 101SD	0.3	MacSeal 6690	0.9
Mod 4 3405	0.1	Mod 4 3405	0.6
3405 M	0.1	Elastoflex 72	0.6
MacSeal 6690	0	Roadsaver 522	0.5
Deery 101ELT	-0.1	Deery 101SD	0.4

Roadsaver 231SD	-0.2	Roadsaver 231SD	0.1
Elastoflex 72	-0.3	Deery 101ELT	-0.2

1.8.2 Standard specification for routed reservoir width

Evaluate a wider routed reservoir dimension (1 in. or 1.25 in.) than the current 0.75 in. specification. Wider routing configurations have been shown to improve sealant extendibility for low temperature applications. The benefits of increasing the reservoir width in South Dakota, however, might be limited because of chip sealing activities that are typically performed the summer following crack sealant installation.

1.8.3 Timing of chip-sealing maintenance

Evaluate a delayed chip-sealing maintenance schedule. The performance of many of the sealants evaluated in this investigation would continue to protect the pavement during this extended time without a chip seal, thereby potentially extending the pavement life through delayed chip sealing maintenance.

1.8.4 Approved Products List evaluation request form - other State DOT history

Modify the materials evaluation request form to specify which states are currently using a material, testing the material, and include the material on their approved product list. This additional and more specific information enables the Department to more clearly interpret the recent performance history of the material.

1.8.5 Approved Products List evaluation request form - requalification requirement.

Include language in the APL that requires a requalification for any changes in formulation, manufacturing process, or manufacturing of materials. This addition would clarify the differences between crack sealant materials Deery 101 and Roadsaver 231, which are currently on SDDOT’s APL with products Deery 101ELT, Deery 101SD and Roadsaver 231SD which were evaluated as part of this investigation.

2.0 PROBLEM DESCRIPTION

Ingress of water into pavements may reduce pavement service life due to wetting of sensitive subsoils or expansion during winter months. Cracking of the pavement surface is common and is one of the primary ways surface water from rain and snowmelt penetrates the road surface, potentially causing damage to the surrounding pavement structure. Transverse cracking is most predominant, especially in areas with large seasonal and diurnal temperature fluctuations, which causes significant expansion and contraction of the pavement surface. Longitudinal cracking generally occurs because of expansive soils or improper joining of adjacent paving lanes during construction. If these cracks are left untreated, or the treatments do not perform well, further deterioration of the cracks can occur progressively over time. In states like South Dakota, where underlying subgrade soils are oftentimes poor, water ingress can lower shear strength and/or cause these soils to swell putting increased stress in the cracked area. Other damage can come from snowplow activity, traffic, or other environmental conditions. Crack sealing and filling operations are part of accepted pavement maintenance programs to help preserve the integrity of the road surface and maintain the life of the pavement. It is therefore important that South Dakota refine its methods of selecting and using crack sealing products in order to efficiently maintain their highway infrastructure.

Preserving and maintaining South Dakota's transportation infrastructure is necessary to provide the most cost-effective use of their resources. A significant investment is made each year to maintain nearly 8,000 miles of pavement throughout South Dakota. Not only does this represent a significant percentage of the department's budget, but the performance of pavement maintenance and preservation measures are readily observed and evaluated by the driving public. Consequently, knowledge of the effectiveness of maintenance techniques is of critical interest to engineers and managers of South Dakota's highways.

Large seasonal temperature changes cause pavement surfaces to undergo significant, repeated contraction and expansion. Thermal cracking (primarily transverse to the direction of traffic) occurs when colder temperatures exceed the elastic limit of the pavement materials. While longitudinal cracks also occur, these cracks are less common and are generally easier to address than transverse thermal cracks. Cracking mechanisms are well understood and best management strategies have been implemented across the United States.

Crack sealing is a relatively low-cost preventive maintenance treatment, but only one of the many forms of pavement maintenance used by State departments of transportation to ensure longevity of their infrastructure. The primary goal of these treatments is to extend the life of the pavement either through prevention of further damage or by repairing already damaged surfaces. Sealing cracks performs both of these functions by preventing further damage due to water ingress and repairing the fissure in the surface. In contrast to most other preventive maintenance techniques, it is now standard practice in areas with cooler climates to install crack sealant in cooler weather when crack widths have expanded. Some advantages of crack sealing are that its relatively low cost when compared to other preventive maintenance treatments, it is an effective means to prevent water infiltration into the pavement structure, and the technology is relatively well understood and widely used. The main disadvantages of crack sealing are its relatively short life span and the possibility of bleeding through overlays.

This research project will support the South Dakota Department of Transportation's motivation to updating their process for selecting and managing crack sealant products on their Approved Products List and review the adequacy of their specifications. The department seeks to update its specifications, selection process, and list of high-performing crack sealants through a field investigation that documented the installation and performance of eight different crack sealants at two different test sites in South Dakota. The overall objective is to ensure that the appropriate and most cost-effective products and installation techniques are selected for use within the state.

3.0 OBJECTIVES

The objectives of this project as stated in the Request for Proposal (in italics) were accomplished as described below.

1. *Evaluate ASTM D6690 Type IV and ASTM D6690 Type IV Modified crack sealants on the SDDOT Approved Products List and promising new crack sealants for their suitability for use in South Dakota*—There are currently six Type IV crack sealing products listed on SDDOT's approved products list, which were approved for use by South Dakota 10-12 years ago. Other viable products available for this application were identified and monitored to determine suitability for use in South Dakota crack sealing applications. Crack sealing materials and installation techniques were evaluated based on information gathered from an extensive literature review; interviews with SDDOT maintenance personnel, SDDOT supervisors and engineers, and crack sealing contractors; an evaluation of existing crack sealing installations in South Dakota; a thorough review of the process by which crack sealing products are selected and managed on the Applied Products List maintained by SDDOT; and a long-term performance evaluation of a variety of crack sealing products on asphalt pavements in South Dakota. The results of this evaluation were used to determine which products and techniques provide the best effectiveness against water intrusion into pavements.
2. *Review the South Dakota Standard Specifications for Roads and Bridges for adequacy in regard to selecting suitable asphalt crack sealants*—Maintaining relevant and current specifications is important to ensure construction materials will perform as expected. SDDOT's specifications for crack sealing materials were reviewed to ensure they are current with the state-of-the-practice. Comparable specifications from regions having similar climate will also be reviewed to increase knowledge on this subject. Information from this review were used to revise and/or augment SDDOT's specification for crack sealing materials to ensure that it is consistent with the current state-of-the-practice.
3. *Review and recommend changes to SDDOT's Approved Product List procedures regarding crack sealants*—The procedures by which crack sealing materials are approved by SDDOT were thoroughly reviewed to ensure that they are able to accurately identify materials that will provide the best effectiveness when properly installed on South Dakota pavements. Likewise, the approval process was reviewed to ensure that a process exists to remove poorer performing materials from the list. Other approval procedures from states and provinces were reviewed to learn how best to manage this process in South Dakota. Information from this review were used to improve and/or supplement SDDOT's procedures for approving crack sealing materials to ensure its usefulness.

4.0 TASK DESCRIPTIONS

The objectives of this research were accomplished through a comprehensive literature review, interviews with SDDOT personnel, results of field evaluations of existing and newly installed crack sealant on asphalt pavements in South Dakota, and a thorough review of South Dakota's process by which crack sealant materials are specified and included on the Approved Product List. From these efforts, a strategy was implemented to determine which crack sealant products and techniques provide the best effectiveness in preventing water ingress into pavements, and ensure that material specifications and approval process is current with the state-of-the-practice.

Information was disseminated during the course of the project to the technical panel through detailed and timely quarterly reports, technical memoranda, and periodic presentations. A final report and presentation were delivered to summarize the results of this research. Each of the tasks outlined in the Request for Proposal are detailed in the subsections that follow. Task 0 was added to describe project management activities.

4.1 Task 0

Project Management

Mr. Eli Cuelho of the Western Transportation Institute (WTI) at Montana State University served as the Principal Investigator for this project from its inception in November, 2016 through June, 2017. Damon Fick of Montana State University served as Principal Investigator from July 1, 2017 through project completion. One of their crucial roles was to manage the project in terms of contractual compliance, budget and schedule, administrative tasks, and communications with SDDOT. The Principal Investigators were the primary contact and assumed all project management responsibilities. This project management was important to ensure that the work proposed was completed on time, on budget, and was high quality. Management was generally achieved through regular communication between the Principal Investigator and research team members. The research team submitted brief and concise quarterly progress reports to SDDOT that described accomplishments, status of the project, and future plans. Major deliverables followed SDDOT reporting requirements and formats and drafts were first sent to SDDOT for review and comment.

4.2 Task 1

Meet with project's technical panel to review the project scope and work plan.

The Principal Investigator met with the Technical Panel in November, 2016 to review the proposed scope and work plan.

4.3 Task 2

Review and summarize literature regarding the specification, installation and performance of ASTM D6690 Type IV and ASTM D6690 Type IV Modified asphalt crack sealants, with an

emphasis on northern United States regions that have large seasonal changes in ambient temperature.

A comprehensive literature search was performed to summarize appropriate practices related to the installation and performance of crack sealant materials that are appropriate for use in colder climates and on asphalt concrete pavements. National and international specifications were reviewed to determine best practices among road managers located in colder climates. Installation practices and performance evaluation techniques were reviewed to determine the best course of action regarding this project. Efforts were made to learn as much as possible about material selection, installation, construction, and performance evaluations for crack sealing materials, as well as techniques of roads relevant to the soils, climate, traffic, and other characteristics of the Upper Great Plains region (South Dakota, North Dakota, Nebraska, Iowa, Montana, Minnesota, and Wyoming). Best management practices of crack sealing were sought from journals, reports, databases, conference proceedings, and other sources. The literature reviews documented methods and specifications for the selection and use of crack sealing materials and installation. The review included an analysis of SDDOT records pertaining to previous use of crack sealing materials and techniques. A large amount of literature available on this subject was identified, thoroughly reviewed, and synthesized to extract information relevant to the challenges faced by South Dakota road managers.

4.4 Task 3

Interview contractors, SDDOT maintenance workers, and supervisory personnel regarding experiences with crack sealing practices and sealant performance.

Engineers, construction managers, and maintenance personnel at SDDOT have extensive experience from decades of applying and evaluating preventive maintenance treatments within South Dakota. Likewise, crack sealing contractors that have experience using this technology have knowledge and ideas about the potential causes of failures or successes. For these reasons, telephone interviews were conducted to learn as much as possible from those involved with crack sealing of pavements in SDDOT. Some of the questions or items of discussion with interviewees included:

- familiarity with various materials and/or techniques,
- experience related to the performance of crack sealants on various pavements,
- identification of problems or challenges,
- qualitative assessment of crack sealing practices within SDDOT,
- ideas for improving crack sealing practices,
- anecdotal data from field evaluations,
- familiarity with specifications and/or guidance procedures.

Interview questions were submitted to the Technical Panel for review and approval prior to interviews. In-person interviews were conducted with SDDOT personnel or contractors at their convenience.

4.5 Task 4

Develop a repeatable protocol for evaluating field performance of existing crack seal installations, field test sections, and future sealing projects.

Evaluating the performance of crack sealing installations was an important component of this investigation. Data from these evaluations can be input into a database maintained by the Department to monitor how well certain materials and techniques perform under different conditions and at different geographic locations. Information collected during crack seal installations consisted of:

- material type and preparation,
- installation technique (routing, cleaning, etc.),
- location (road, mileposts, etc.),
- pavement type and age,
- pavement temperature
- ambient conditions,
- contractor name,
- date of installation,
- initial crack width, and

Once the crack sealants were installed, periodic assessments were conducted to evaluate the performance over time. Data collected during site visits included:

- date of evaluation,
- photographs of crack lengths documenting adhesive, cohesive, or pullout failures of the sealant material. Individual failure types were divided by the total length of the crack to determine percent length affected,
- crack width – determined by physical measurements between two survey nails installed on several cracks during the crack sealant installation at each test site,
- weathering of sealant – determined through visual assessment,
- sealant wear – determined through visual assessment,
- presence of bubbling – determined through visual assessment,
- presence of stone intrusion– determined through visual assessment,
- secondary cracking – presence was noted and the length of secondary cracking was documented,
- pavement temperature – determined using infrared temperature probe, and
- ambient weather conditions.

The performance of seven full-width transvers cracks were documented for each crack sealant material during the site visits to ensure a statistically relevant and consistent sample. Individual cracks were later evaluated by reviewing the photographic evidence collected during each site visit. Data was recorded on paper during the site visits and later transferred to an electronic format for storage.

4.6 Task 5

Submit a technical memorandum and meet with the project's technical panel to present the results of Tasks 2-4 and secure approval of the proposed performance evaluation protocol.

Technical memoranda are an important means of summarizing and documenting what was accomplished. A concise summary of Tasks 2-4 was submitted to the Technical Panel and included: 1) the results of the literature review, 2) a summary of the interviews with contractors, engineers, and maintenance personnel, and 3) the test protocol for evaluating existing and future crack sealing installations. Information contained in the technical memorandum was discussed in detail during a web-based, interactive teleconference led by the Principal Investigator.

4.7 Task 6

Evaluate past field performance of a representative number of installation of sealants on SDDOT's Approved Products List to characterize failure mechanisms and material performance, and summarize results along with information available from SDDOT regarding sealant type, asphalt mixture, age, etc.

The performance of several crack sealing installations was reviewed during a site visit by the Principal Investigator after the kick-off meeting. Six sites were visited, and a quick survey of these installations was made to assess the general performance of the crack sealant. Available documentation related to the construction and materials at these sites was collected and reviewed. The six sites were selected during the kick-off meeting.

4.8 Task 7

Based on the findings of prior tasks, prepare a field-testing plan including construction plan notes for installation of no more than ten currently approved or new crack sealants on each of two SDDOT-contracted crack sealing projects with differing asphalt pavement types.

A formal testing plan was developed to test various crack sealing products as part of the long-term evaluation of this project. This plan included detailed instructions and construction notes to SDDOT maintenance personnel regarding the installation of various sealants on two highways in South Dakota that have different kinds of asphalt pavements. The location of these two sites, as suggested by SDDOT, were on highway SD 50 between Tabor and Yankton, and highway US 14 west of Miller, SD. Information considered for the selection of the two test sites included: location:

- asphalt type,
- age and condition of pavement,

- AADT,
- frequency of cracks,
- width of cracks,
- temperature and weather conditions, and
- anticipated installation technique.

Crack sealing materials were selected using information gathered from Tasks 1, 2, and 3 and through a search of crack sealing materials currently available on the market. Final determination of the locations of the test sections and the eight crack sealing materials to be employed were done in consultation with the Technical Panel.

4.9 Task 8

Submit a technical memorandum and meet with the technical panel to present the results of Tasks 6-7 and secure approval of the field-testing plan.

A concise summary of Tasks 6 and 7 was submitted to the Technical Panel for review and approval of the testing plan associated with the field evaluation. This memorandum included: 1) the results of the existing crack sealant evaluation and 2) the testing plan for the field performance evaluation. Information contained in the technical memorandum was discussed in detail during a web-based, interactive teleconference led by the Principal Investigator.

4.10 Task 9

Observe and document the installation of all crack sealants at both SDDOT-contracted crack sealing projects.

The Principal Investigator for this project documented the preparation and cleaning of the cracks and installation of the crack sealant at the two test sites selected as part of Task 7. Crack sealants were installed at both sites during the same week. Safety protocols were followed while photographic records of the installation process were collected. Other data collected includes:

- installation technique (routing, cleaning, etc.),
- temperature of sealant materials during application,
- adherence to suggested manufacturer recommendations,
- location (road, mileposts, etc.),
- pavement type and age,
- pavement temperature
- ambient conditions,
- contractor name,
- date of installation,
- initial crack width, and

The locations of individual cracks were documented using MRM locations collected with GPS equipment available in SDDOT field vehicles.

Samples of each crack sealant installed were collected for quality assurance purposes. Testing was conducted by the SDDOT Materials Lab and results included in the project documentation.

4.11 Task 10

Observe, evaluate, and report the field performance of all installed field test crack sealants over a time interval spanning two winter/spring freeze-thaw cycles, including evaluations during sustained extreme summer and winter temperatures.

Four performance evaluations were conducted during the two years following installation of the crack sealant at the two test locations using the evaluation protocols established in Task 5. the evaluations occurred at approximately six-month intervals following installation on September 6-7, 2017:

- Evaluation 1 – February 10-11, 2018
- Evaluation 2 – June 15-16, 2018
- Evaluation 3 – March 21-22, 2019
- Evaluation 4 – August 17-18, 2019

A database was created to house all data collected from the field evaluations.

4.12 Task 11

Review the South Dakota Standard Specifications for Roads and Bridges and recommend possible change regarding asphalt crack sealants.

New materials, technologies, specifications and construction practices are continually being introduced into this industry. South Dakota’s crack sealing specifications, Sections 350 and 871 in the SDDOT’s Standard Specifications for Roads and Bridges (2015) were reviewed. Design and construction documentation from other states was also collected to provide foundational material for a framework to document South Dakota’s crack sealing guidelines and specifications. Wyoming, Montana, North Dakota, Minnesota, Iowa, and Nebraska were the seven neighboring states selected. Resources for these states were documented for future use by SDDOT personnel.

4.13 Task 12

Review SDDOT’s current method for including crack sealants on the SDDOT Approved Products List and recommend possible changes to improve the usefulness of the APL.

Maintaining a relevant and up-to-date list of approved products is a good method of ensuring quality construction materials are used. Materials must meet certain criteria to be included on this list. Generally, materials are accepted to lists like these based on:

- An acceptable performance history

- The use of historically quality materials
- Relative small-cost
- Materials not requiring specialized testing equipment for acceptance testing

A process for removing poor-performing materials from the list must be included in the process. The National Transportation Product Evaluation Program (NTPEP) also maintains a list of approved products that have met acceptance criteria established by AASHTO. South Dakota's product evaluation procedure was reviewed to improve the process by which materials are approved for use in the department's construction jobs.

4.14 Task 13

Submit a technical memorandum and meet with the technical panel to present the results of Tasks 9-12.

A concise summary of Tasks 9-12 was submitted to the Technical Panel. This memorandum included: 1) a summary of the observations made during installation of the test crack sealant, 2) a summary of the periodic evaluations made during the field evaluation, 3) a brief overview of the review of the standard specifications associated with crack sealing products, and 4) a summary of the review of the approval process for crack sealing materials including any recommendations for improvement. Information contained in the technical memorandum was discussed in detail during a web-based, interactive teleconference led by the Principal Investigator.

4.15 Task 14

In conformance with Guidelines for Performing Research for the South Dakota Department of Transportation, prepare a final report summarizing the research methodology, finding, conclusions and recommendations, including change to any specifications and Approved Products procedure.

A final report was prepared to document all aspects of the research including a summary of each of the tasks, pertinent results, and conclusion and recommendations. The final report provided the detailed results of the literature review, interviews with SDDOT personnel, results of the field evaluations of crack sealing performance along with a summary of the testing plan, a summary of the specifications, and, the updated process for including and retaining crack sealing products on SDDOT's approved product list. An executive summary was prepared to concisely communicate the purpose, general approach, and significant findings of the study. The format of the report followed the most recent SDDOT guidelines. A draft of the report was submitted to the Technical Panel with sufficient time for their review and final acceptance.

4.16 Task 15

Make an executive presentation to South Dakota Department of Transportation Research Review Board at the conclusion of this project.

The Principal Investigator presented the methodology and findings of the project to the SDDOT Research Review Board. The presentation summarized all aspects of the project associated with the selection, installation, evaluation, management and performance of crack sealing operations on asphalt pavements in South Dakota.

5.0 LITERATURE REVIEW

Crack sealing of asphalt pavements is a preventative maintenance technique that helps mitigate the infiltration of water into the pavement surface, which, in many cases, causes damage to the structural integrity of the road. If cracks are left untreated, or the treatments are not effective, further deterioration of the cracks may occur, although the amount of damage depends on the sensitivity of the supporting materials, traffic levels, and other factors. In areas that are sensitive to water infiltration, crack sealing and filling operations help protect against premature pavement damage and deterioration. In these cases, it is important to utilize a method of practice that will most effectively address the problem. Previous research on the effectiveness and best methods of crack sealing were examined along with specifications from other states with a similar climate to the Upper Great Plains region to determine how best to seal cracks in pavements. The following aspects of crack sealing that were identified in the literature review are summarized below: 1) construction and material requirements within state and province standard specifications, which included preparation of the crack by routing and/or cleaning, installation methods, and types of materials available and/or approved, 2) testing specifications associated with crack sealing, 3) material and field performance of crack sealing and its effect on pavement condition, and 4) methodologies used to evaluate the performance of crack sealing.

5.1 Construction and Material Requirements from States and Canadian Provinces

U.S. and Canadian specifications were reviewed to determine the state-of-the-practice for crack sealing asphalt roadways among road managers located in colder climates. Specifications from Alberta, British Columbia, and Ontario were reviewed, as well as Colorado, Minnesota, Montana, Nebraska, New Hampshire, New York, South Dakota and Wyoming. Generally, this review focused on construction requirements (routing, cleaning, and timing) and materials within each state's standard specification. Approved Products Lists (or Qualified Products Lists) were also reviewed for each state to determine which products are approved by these same agencies. Finally, any standard tests for determining proper materials were also reviewed and summarized.

5.1.1 <u>Routing</u>

Routing is a widely used technique that has been shown to improve the performance of the sealant by up to 40 percent (SHRP, 1994 cited in NDOR, 2002). It has been further shown to outperform the clean and seal technique of unrouted cracks (Cuelho and Freeman, 2004; Shuler, 2009). The size and shape of the rout has also been shown to affect the performance and service life of the sealant materials. Many different rout configurations have been tested to determine the best performing geometry. Several common rout and sealant configurations are shown in Figure 1 (SHRP, 1994). Square routs are very common and are a relatively effective configuration. In a study conducted in Montana by Cuelho and Freeman (2004), a square rout with a 'band-aid' exceeded other configuration's performance along with the shallow and flush method. Wide and shallow routing configurations have also been shown to improve sealant extendibility for low temperature applications (Ponniah, Kennepohl 1996) and to outperform other rout configurations (Chong, 1990; Cuelho and Freeman, 2004; Filice, 2003; Fer and Kavanagh, 2006). According to a laboratory study coupled with a finite element analysis, seal geometries with a width to depth ratio of greater than 1.5 were shown to reduce strains on the sealant (Khuri and Tons, 1992). A 3:1 width to depth ratio is recommended for transverse cracks by the Montana Department of Transportation (MDT, 2014). In Canada, a width to depth ratio of greater than one is recommended as it shows improved performance over other rout configurations (Masson et al., 2003). Recessed sealant configurations have been shown to have mixed performance. In a Montana study, the square and recessed sealant configuration was vulnerable to adhesion failures (Cuelho and Freeman, 2004); however, studies conducted in Texas, Kansas, Washington and Iowa showed the square or shallow recessed 'band-aid' configurations worked better than other techniques, (FHWA, 1999; Shuler, 2009; Smith and Romine, 1999). Whether to rout depends on the width of the crack. Based on specifications reviewed from northern states and Canada, it is recommended to rout cracks with widths between about ⅛ in. to 1 in. A summary of routing practices from these states is provided in Table 1. Based on an extensive literature review and survey conducted by Ragab et al. (2013), crack wider than about ¾-inch should not be routed, and that routing configurations vary widely from state to state and in Canada.

5.1.2 Cleaning

Cleaning is also an important component of preparing the crack for sealant. The bituminous sealants need a clean dry surface to ensure proper adhesion to the asphalt. Compressed air, vacuuming, or hot air lances are commonly used to clean cracks. An air compressor capable of providing a high volume of dry air is the most common method specified by departments of transportation to ensure that the crack is clean and dry. Based on an extensive literature review and survey conducted by Ragab et al. (2013), all states and provinces require cracks to be cleaned and dried using either a hot air lance or compressed air. Most agencies do not allow the use of leaf blowers because of the low pressure of the air expelled from the blower. In a field and laboratory study conducted by Masson and Lacasse (1999), the use of hot air lances at 2400°F correlated with poorer performance of the sealants, most likely due to overheating the binder face causing it to become more brittle. This same study showed that decreasing the heat of the air lance from 2400°F to 900°F prevented overheating while also allowing the removal of moisture from the crack. Crack cleaning specifications from northern states and Canada are summarized in Table 2.

5.1.3 Crack Sealants

There are many crack sealing materials available on the market for sealing asphalt pavements in colder environments. Crack sealants in cold climates are normally hot applied asphalt-based materials. Specifications associated with these materials are geared toward the selection of materials appropriate for a particular climatic condition. According to ASTM D6690 (Joint and

Crack Sealants, Hot Applied, for Concrete and Asphalt Pavements), in general, crack sealant materials are to consist of materials that:

1. will form an effective seal against water and other foreign particles during repeated thermal expansion and contraction,
2. will resist flow from the crack or sticking to tires,
3. can be brought to a workable consistency without containing excessive air bubbles or discontinuities, and without damage to the material, and will retain these characteristics for at least 6 hours at the recommended temperature during installation.

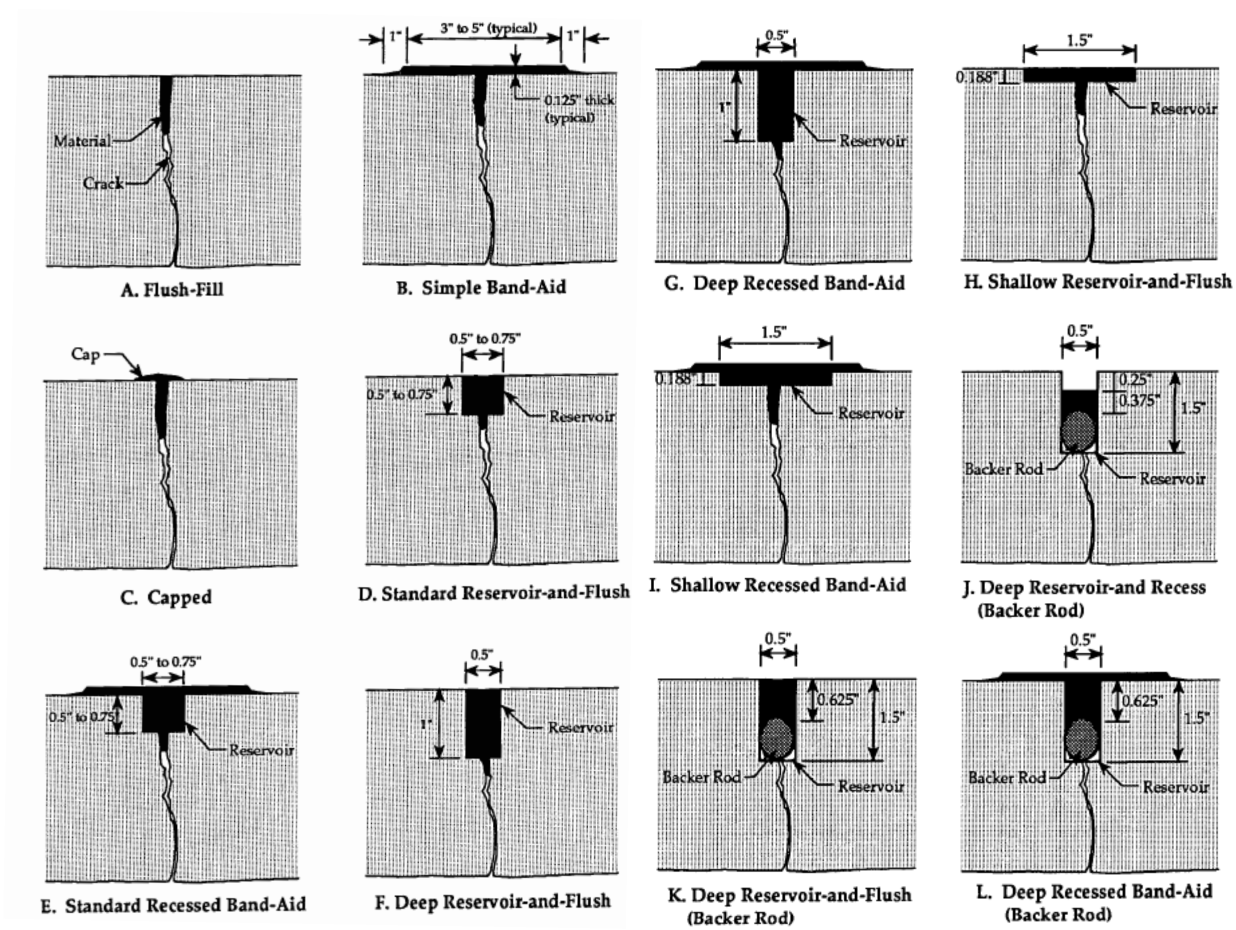


Figure 1 Common Rout and Sealant Configurations (from SHRP, 1994).

Balancing workability, flexibility, adhesion, and durability is challenging given the large number of variables associated with this application. ASTM D6690 outlines four types (Types I, II, III and IV) of asphalt-based crack sealants. Types I is for moderate climate, Types II and III are for most climates (yet cooler than Type I), and Type IV is for very cold temperatures. Type IV is required by South Dakota's specifications because of the severe winter weather across the state. A list of available Type IV products assembled from an Internet search of manufacturer product data sheets is summarized in Table 3 in alphabetical order by manufacturer. Products from states and Canadian provinces that meet ASTM D6690 Type IV (as determined through Approved Products Lists or equivalent) are identified at the bottom of Table 3. Based on an extensive literature review and survey conducted by Ragab et al. (2013), 15 of 26 states and provinces that participated in the study indicated that materials must meet the specifications outlined in ASTM D6690 or AASHTO M324 and/or ASTM D5329.

Table 1: Routing requirements for northern states and Canada

	Recommended Minimum Crack Width (in.)	**Rout Width x Depth (in.)**
Alberta[1]	0.07 – 1.0	1.6 x 0.4
British Columbia[2]	< 0.63	0.63 x 0.75 – 1.0
Colorado[3]	0.125 – 1.0	Don't Rout
Minnesota[4]	≤ 0.75	0.75 x 0.75
Montana[5]	0.2 – 1.0	1.5 x 0.5
Nebraska[6]	< 0.375	0.5 x 0.75 – 1.0
New Hampshire[7]	0.125 – 0.75	0.75 x 0.625
New York[8]	0.125 – 1.0	0.625 x 0.5
Ontario[9]	< 0.79	1.6 – 2.0 x 0.3
South Dakota[10]	< 0.75	0.75 – 0.875 x 0.75 – 0.875
Wyoming[11]	0.125 – 0.5	0.75 x 0.75

[1] Alberta, 2010
[2] BC MTI, 2016
[3] CDOT 2011
[4] MnDOT, 2016
[5] MDT, 2014
[6] NDOR, 2007
[7] NHDOT, 2016
[8] NYDOT, 2013
[9] OPSS, 2015
[10] SDDOT, 2015
[11] WYDOT, 2010

During sealing operations, caution should be taken to prevent overheating the sealant which may cause the sealant to prematurely breakdown or decrease the performance (Masson et al., 1998). Manufacturers' recommendations should be followed to achieve the best results.

5.1.3.1 Environmental Temperature and Moisture Considerations

Historically, most cracks are sealed in the spring, fall or winter when the crack is near its widest point. Sealing during this period ensures a balance of extension and compression of the sealant due to seasonal temperature variations, which helps ensure the sealant is not overextended or over compressed. An illustration of this effect is shown in Figure 2 (Decker, 2014). Crack sealant may crack or tear to relieve strain during cooler times of year when sealants are stretched, if the sealant materials have lost their resiliency. Alternatively, in the summer when crack widths are at their narrowest point, a healing effect has been shown to occur. However, in most northern states this healing commonly occurs after the wettest time of the year, and water would have already had the opportunity to infiltrate the pavement (Cuelho and Freeman, 2004; Shuler, 2010b). Ambient temperature requirements are used to minimize excess bulging and stretching of the crack sealant. Temperature-related specifications from northern states and Canadian provinces are summarized in Table 4. Sealing operations are commonly conducted in the temperature ranges of 35°F to 70°F.

Based on an extensive literature review and survey conducted by Ragab et al. (2013), most states and provinces indicate that sealants may be installed at air temperatures above 40°F. Many sealant manufacturers (Crafco RoadSaver 522, Crafco RoadSaver 231, W.R. Meadows #3405-M, W.R Meadows Sof-Seal, Right Pointe #3405-M, Deery 101ELT) recommend a minimum installation temperature of 40°F to guard against the presence of water or ice in the crack which may negatively affect adhesion. Moisture in the crack does not allow the bituminous sealant materials to properly adhere to the pavement, thereby reducing its effectiveness. Great care must be taken to ensure that the crack is completely dry before sealing. Most agencies warn against sealing when rain is imminent. South Dakota's specifications do not allow crack sealing if the humidity is above 75 percent. Montana Department of Transportation recommends that the humidity be below 50 percent (MDT, 2001).

Table 2: Specified cleaning methods from northern states and Canada

State/Province	Cleaning Equipment
Alberta[1]	No specification
British Columbia[2]	Hot air lance
Colorado[3]	Hot air lance
Minnesota[4]	Compressed air, Hot air lance, Vacuum
Montana[5]	Compressed air
Nebraska[6]	Compressed air, Hot air lance, Sandblasting, Brushing
New Hampshire[7]	Hot air lance
New York[8]	Compressed air, Hot air lance
Ontario[9]	Hot air lance
South Dakota[10]	Compressed air
Wyoming[11]	Compressed air Hot air lance

[1] Alberta, 2010
[2] BC MTI, 2016
[3] CDOT 2011
[4] MnDOT, 2016
[5] MDT, 2014
[6] NDOR, 2007
[7] NHDOT, 2016
[8] NYDOT, 2013
[9] OPSS, 2015
[10] SDDOT, 2015
[11] WYDOT, 2010

5.2 Testing Specifications

Type IV sealants are tested under the most severe conditions (200 percent extension at -29 degrees C). ASTM D5329 (Standard Test Method for Sealants and Fillers, Hot Applied, for Joints and Cracks in Asphalt Pavements and Portland Cement Concrete Pavements) contains multiple procedures to determine conformance of hot-applied, field molded sealant materials. Tests from this standard include:

Table 3: Available asphalt-based crack sealants that meet ASTM D6690 Type IV specifications

	Sealant	Manufacturer
A	ColJoint 6690 Type IV	Colas Solutions
B	Deery 101	Crafco, Inc.
C	Deery 101-ELT	Crafco, Inc.
D	Roadsaver 231	Crafco, Inc.
E	Roadsaver 522	Crafco, Inc.
F	Elastoflex 6690 Type 4	Maxwell Products, Inc.
G	Elastoflex 71	Maxwell Products, Inc.
H	Elastoflex 72	Maxwell Products, Inc.
I	Elastoflex 71 WY (Wyoming)	Maxwell Products, Inc.
J	Macseal 6690-4	McAsphalt Industries Ltd.
K	Macseal 6690-4 Mod	McAsphalt Industries Ltd.
L	Dura Fill 3405 LM (K)	P&T Products, Inc.
M	Dura-Fill 3405 LM (M)	P&T Products, Inc.
N	Dura Fill 3725 (Minnesota)	P&T Products, Inc.
O	#3405 LM	Right Pointe Company
P	#3405 Modified	Right Pointe Company
Q	CrackMaster 3405 LM	Seal Master
R	CrackMaster 3725	Seal Master
S	3405-M	W.R. Meadows, Inc.
T	Sof-Seal	W.R. Meadows, Inc.

Alberta[C, E, K]
British Columbia[C, E, H, K]
Colorado[P]
Minnesota[C, E, K, N]
Montana[C, E, H, K, P]
Nebraska[D, J, O]
New Hampshire[B, D, J]
New York[D, L, P]
Ontario[K]
South Dakota[B, D, K, S, T]

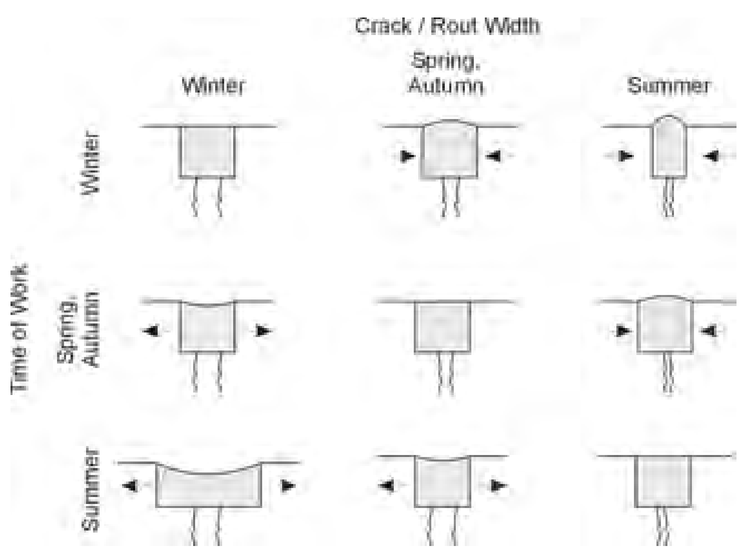


Figure 2 Importance of sealing in spring and fall illustrated, (Decker, 2014).

1. Cone Penetration (non-immersed) – measure of the consistency of the material, where higher values indicate a softer consistency. Cone penetration of Type IV materials is tested at 25°C.

2. Flow – measure of the ability of a sealant to resist flow from the crack at greater ambient temperatures.
3. Bond to Concrete (non-immersed) – measure of the ability of the sealant to bond to concrete.
4. Bond to Concrete (immersed) – measure of the ability of the sealant to bond to concrete after being immersed in water. Only used to evaluate Type III sealants.
5. Resilience – measure of the ability of the sealant to recover after a steel ball has been forced into its surface.
6. Resilience (oven aged) – measures the ability of the sealant to rebound a steel ball after it has been aged in an oven for seven days.
7. Asphalt Compatibility – determines the compatibility of the sealant to asphalt pavement.
8. Artificial Weathering – measure of the sealant's ability to withstand weathering (from xenon arc or fluorescent UV light).
9. Tensile Adhesion – measure of the elongation of the sealant prior to failure when adhered to concrete.
10. Flexibility (a.k.a. Rotational Viscosity) – measure of the ability of the sealant to be bent around a mandrel after being exposed to heat aging.

Table 4: Ambient temperature requirements for northern states and Canada

State/Province	Temperature (°F)
Alberta[1]	> 50
British Columbia[2]	> 50
Colorado[3]	> 40
Minnesota[4]	40 – 85
Montana[5]	35 – 120[†]
Nebraska[6]	N/S
New Hampshire[7]	> 50
New York[8]	> 40
Ontario[9]	> 50
South Dakota[10]	40 – 85
Wyoming[11]	40

[1] Alberta, 2010
[2] BC MTI, 2016
[3] CDOT 2011
[4] MnDOT, 2016
[5] MDT, 2014 (mat temp.)[†]
[6] NDOR, 2007
[7] NHDOT, 2016
[8] NYDOT, 2013
[9] OPSS, 2015
[10] SDDOT, 2015
[11] WYDOT, 2010

Currently, 1, 3, 5, and 7 are used in the specification limits for Type IV crack sealant materials, as listed in Table 5. Variations of these properties have a significant impact on their field performance. Softening point is also evaluated, which provides an indication of the temperature at which the sealant may become overly soft and tacky after being applied in the field. South Dakota currently uses ASTM D6690 to specify appropriate Type IV crack sealing materials, with an additional criterion of 9.35 lb/gal compared with ASTM D6690 specified .

Table 5: Specifications for Type IV crack sealant (from ASTM D6690)

Test	Acceptance Criteria
Cone Penetration at 25°C	90-150
Softening Point (°C)	≥ 80
Bond (non-immersed)	Three 12.5 ± 0.2 mm specimens, Pass 3 cycles at 200% extension at -29°C
Resilience (%)	≥ 60
Asphalt Compatibility	Pass†

†No failure in adhesion, formation of any oily exudate at the interface between the sealant and asphaltic concrete or other deleterious effects on the asphaltic concrete or sealant when tested at 60°C

Multiple studies indicated that the ASTM D6690 Type IV specification do not relate well to field performance. Several studies have proposed that additions or substitutions be made to this specification to more adequately predict field performance, as summarized in Table 6 (Al-Qadi et al., 2009; McGraw and Olsen, 2007; Decker, 2014; Truschke et al., 2014; Yildirim et al., 2006). Sealants such as RoadSaver 231 (Crafco, Inc.) performed well in the field but failed to meet ASTM D5329 specifications (Cuelho and Freeman, 2004). According to a study conducted by Al-Qadi et al. (2009), material properties that have been most closely related to field performance include creep stiffness, extendibility, and apparent viscosity at the manufacturer's recommended installation temperature. An important component of this research was that the sealant materials were aged using a vacuum oven aging procedure to simulate weathering of the sealant in the field prior to testing. The only exception to this is the apparent viscosity test which is performed on un-aged sealant. Proposed additions to ASTM D6690 Type IV specifications include: the modified bending beam rheometer test (BBR) used to determine creep properties at low temperatures, the crack sealant direct tension test (DTT) used to evaluate strain properties at low temperatures, and the dynamic shear rheometer test (DSR) used to characterize tracking resistance at high temperatures. These three tests have been shown to correlate well with field performance of sealants in cold climates. AASHTO has adopted the following tests that more accurately relate to field performance, as proposed by Al-Qadi (Truschke, 2014):

- TP 85-10 – Apparent Viscosity of Hot-Poured Crack Sealant Using Brookfield Rotational Viscometer RV Series Instrument
- TP 86-10 – Accelerated Aging of Bituminous Sealants and Filler with a Vacuum Oven
- TP 87-10 – Measure Low Temperature Flexural Creep Stiffness of Bituminous Sealants and Fillers by Bending Beam Rheometer (BBR)
- TP 88-10 – Evaluation of Low-Temperature Tensile Property of Bituminous Sealants by Direct Tension Test

- TP 89-10 – Measuring Adhesion of Hot-Poured Crack Sealant Using Direct Adhesion Tester
- TP 90-10 – Measuring Interfacial Fracture Energy of Hot-Poured Crack Sealant Using a Blister Test

Table 6: Alternate crack seal tests from literature

Study	Apparent Viscosity AASHTO TP 85-10	Direct Shear Rheometer AASHTO T315	Bending Beam Rheometer AASHTO T313	Direct Tension Test AASHTO TP 88-10	Direct Adhesion AASHTO TP 89-10
Al-Qadi et al. (2009)	X	X	X	X	X
McGraw and Olsen (2007)			X		
Decker (2014)	X	X	X	X	X
Truschke et al. (2014)	X		X	X	X
Yildirim et al. (2006)		X	X		

Referring to the BBR test, a maximum stiffness of 24 MPa at 240 sec and a minimum average creep rate of 0.31 mm/mm/sec were recommended as they related to good performance in the field for sealants in low temperature areas (Al-Qadi et al., 2009). In a Canadian study, eight sealants were testing using the DSR and BBR tests. Field performance was then observed and it was found that creep stiffness (from the BBR) related directly to sealant field performance. From the results of creep stiffness at 60 seconds (S_{60}) maximum threshold value of 10 MPa at -30°C was recommended to discern between sealants with poor performance and good to satisfactory performance (Soliman et al., 2008).

Sampling of materials from the field and sampling from individual containers can also introduce errors in the test results. In a study conducted by Masson et al. (2005), tests were run on samples taken from multiple batches of sealant, and from several areas within a single container. It was found that sealant properties vary throughout the same lot of material depending on how the sampling was done. Care should be taken to ensure that the samples that are procured for testing are representative of what is actually being installed.

5.3 Material and Pavement Performance Considerations

Many field studies have been conducted to evaluate the performance of crack sealing materials and installation techniques. Fewer field studies have focused on the effect crack sealing has on the performance of the roadway itself. The two subsections below provide a brief overview of the results from some of the most relevant studies in terms of how the crack sealant itself performs in the field and how crack sealing affects the performance of the pavement.

5.3.1 Material Performance

Dozens of research projects and university studies have been conducted during the past several decades to understand and quantify the field performance of pavement crack sealants. Results are sometimes mixed due to the many variables encountered in this application, however, some materials and techniques generally seem to work better than others. A brief synopsis of many of the larger efforts during the past few decades is provided in Table 7. Based on previous research, low-modulus, hot pour materials outperformed many other sealants in side-by-side comparisons (Cuelho and Freeman, 2004; Fer and Kavanagh, 2006; Filice, 2003; AASHTO NTPEP, 2009). Cold-pour sealants that have been tested in the field have been shown to be a very ineffective and costly treatment option with some sealants failing after only a year of service or less. Most agencies reported a typical sealant lifespan of 3 to 5 years, (Regab et al., 2013; Truschke et al., 2014; NDOR, 2002), although some states have measured sealant service lives as long as 10 years depending on traffic volume, elevation, conditions when sealant was applied, etc. (Truschke et al., 2014). According to the survey conducted by Decker (2014) in the *NCHRP Best Practices for Crack Treatments for Asphalt Pavements*, the majority of responses (54-55%) indicated that the typical lifespan of crack sealing on major and minor roads is around 5-10 years.

5.3.2 Pavement Performance

Clear, quantitative assessments of whether crack sealing indeed slows the deterioration of the pavement structure are rare and limited. Overall, information from interviews and literature reviewed by Hand et al. (2000) concluded that "all of these efforts revealed little quanitative evidence to prove the cost-effectiveness of joint/crack sealing." The extension of pavement life provided by crack filling and sealing still seems to be lacking. Conflicting results have been found when evaluating the cost effectiveness of crack sealing with respect to its effect on pavement performance. A brief summary of research efforts is presented in Table 8.

An extensive cost effectiveness study was performed in Ohio on more than 700 test sections that were each 1000 feet long (Rajagopal, 2011). Variables considered by the study included pavement type, type of aggregate in the pavement, and the condition of the pavement before crack sealing. Control sections (no crack sealant was applied) were used as comparisons. Pavement condition ratings (PCRs) were determined annually by the same person throughout the study to eliminate variability in data collection (greater PCR numbers indicate better performing pavements). Crack sealing operations were conducted at various times on a diverse range of pavement conditions. The study showed that crack sealing is cost effective for pavements with a PCR in the range of 66-70, and the maximum performance gain is achieved in the range of 66-80. The study also indicated that earlier treatments provide greater improvement. According to Peshkin et al. (2004), crack sealing treatments should be applied to pavements that are approximately 2-4 years old. Two other studies stated that a second rout and seal application should be performed between the eighth and ninth years of the pavement service life to maximize the benefit of initial treatment (Chong, 1990;

Ponniah and Kennepohl, 1996). Another study indicated a 13 percent savings over a thirty-year period when cracks were sealed in the fourth and eighth years of the pavement service life, when compared to the cost of full pavement rehabilitation as the only other alternative considered (Ponniah and Kennepohl, 1996). Timing as well as different techniques, pavement type, cleaning operations, rout configurations and materials all play a role in the effectiveness of the sealant. Crack sealing had no substantial effect on long-term roughness, fatigue cracking or rutting in a study on 81 test sites across the United States and Canada (Hall et al., 2003). No difference in roughness, in terms of the International Roughness Index (IRI), was measured during a Montana study (Cuelho and Freeman, 2004). According to a study conducted by the Ministry of Transportation in Ontario Canada, crack sealing should provide extended pavement service life of at least two years, as illustrated in Figure 3 (Ponniah and Kennepohl, 1996).

Table 7: Brief synopsis of the field performance of crack sealing materials

Author(s), year	Brief Synopsis	Relevant Results / Conclusions
Cuelho and Freeman, 2004	Montana study with 4 test sites, 11 materials, and 6 installation techniques; cost effectiveness study	Crafco RoadSaver 522 and the shallow and flush technique were the most cost effective based on crack sealing performance.
Decker, 2014	State-of-the-art and practice report for NCHRP	Literature review; survey; best practices
Erickson, 1992	Four sealant materials were evaluated over 1 year in Washington state.	Deery Flex-A-Fill and Crafco RoadSaver 221 performed best.
Fer and Kavanagh, 2006	12 sealants evaluated for 2 years.	Crafco RoadSaver 522 was the best followed by Crafco RoadSaver 244.
FHWA, 1999	Field evaluations in TX, KS, WA, IA, and Ontario to determine most economical and effective crack sealing material and technique.	Asphalt rubber placed in the standard or shallow recessed rout performed the best. Standard, recessed band-aid showed longest estimated service life followed closely by shallow recessed band-aid. Quality control is crucial to good performance.
Filice, 2003	Field performance on 8 materials over 7 years.	Husky 1611, Crafco 522 and Koch 9030 performed the best.
Li and Li, 2015	Seal band product as alternative to hot poured crack sealant	Faster to install, tested using different lab tests, no field evaluation information
Masson et al., 2007	Tests for assessing tracking resistance	None of tests tried could accurately predict trackability
AASHTO NTPEP, 2009	12 materials tested in Minnesota, ¾ x ¾ rout size	Data indicates that Deery 101-ELT, W.R. Meadows 3405-M and Crafco 522 performed best.
Ponniah and Kennepohl, 1996	Manitoba crack sealing effectiveness and cost-benefit analysis	Rout configuration of 4:1 (40 mm wide to 10 mm long) performed best.
Ram and Peshkin, 2014	Preventive maintenance research for Michigan	Good benefit-cost, but not able to improve other widespread pavement distresses
Regab et al., 2013	Literature review of state with colder climates	47% of agencies reported sealant life of 3-5 yrs.
Shuler, 2009	Study of multiple installation techniques, three sealants	Performance suffers when heat lance is used. Routing improves performance, overbanding helps performance. Harder product worked better than softer indicating that specifications may not be accurate
Shuler, 2010a	Literature review, full scale test sections to monitor crack sealant performance.	Crack sealing was beneficial
Shuler and Hessling, 2011	Effects of deicers and elevation on crack sealing effectiveness in Colorado	Sealants exposed to MgCl at higher elevations showed higher degradation

Table 7 (Cont.)

Author(s), year	Brief Synopsis	Relevant Results / Conclusions
Shuler and Ranieri, 2009	Six installations evaluated	Overbanding technique performed best regardless of how crack was cleaned
Soliman, 2008	Laboratory testing to determine relationship to field performance.	Good correlation between sealant performance and the DSR and BBR tests.
Truschke, 2014	Colorado literature review and interviews	Most agencies reported life of 3-5 yrs.
Wilde and Johnson, 2009	Studied roughness characteristics of overlays atop crack sealed pavements	Larger reservoir geometry performed least favorably. MnDOT 3725 sealant performed worst. Best geometries were narrower and did not use overband.
Yang et al., 2010	Laboratory testing (DTT and BBR) to determine relationship to field performance.	Recommended stiffness at 240 s of 25 MPa and average creep stiffness of 0.31 mm/mm/s.
Yildirim et al., 2003	3-year study comparing hot and cold pour sealants in Texas	Excellent performance from hot pour; drastic decline in cold pour performance
Yildirim et al., 2006	33 tests sections monitored over 4 years.	Hot pour sealants better than cold pour.
Yildirim et al., 2010	33 test sections. 7 hot pour sealants and 3 cold pour.	Hot pour service life was 26-42 mo. while cold pour service life was 10-16 mo.

Table 8: Brief synopsis of the effect of crack sealing on pavement performance

Author(s), Year	Brief Synopsis	Relevant Results/Conclusions
Bae et al., 2007	Field study considering IRI; transverse thermal cracking; longitudinal profile	Transverse thermal cracking causes significant IRI readings in smooth or newer HMA pavements. The more severe the crack, the greater the IRI reading. Thus it is worthwhile to maintain and fill the cracks.
Chong, 1990	Cost-effectiveness study; extension of pavement life; optimum timing	Optimum timing is from 3rd to 5th years for initial treatment and 8th to 9th years for follow-up treatment.
Cuelho and Freeman, 2004	Montana study with 4 test sites, 11 materials, and 6 installation techniques. Cost effectiveness study	Improvement in pavement performance was not evident from crack sealing based on IRI measurements.
Hall et al., 2003	Long-term study using LTPP data	Crack sealing did not demonstrate benefit in terms of IRI, rutting or cracking.
Peshkin et al., 2004	Optimal timing of treatment	First treatment at pavements age of 2-4 years
Ponniah and Kennepohl, 1996	Manitoba crack sealing effectiveness, cost-benefit analysis, life-cycle cost analysis	Crack sealing provides service life extension of at least 2 years. Overall long-term cost savings when cracks are sealed; erosion at bottom of cracks more prevalent when not sealed; lipping and cupping more frequent;
Rajagopal, 2011	Over 700 test sections evaluated over 9 years in Ohio.	Crack sealing can extend pavement service life by up to 1.85 years.
Zinke et al., 2005	Literature review	Crack sealing can extend pavement service life by up to 2 years.

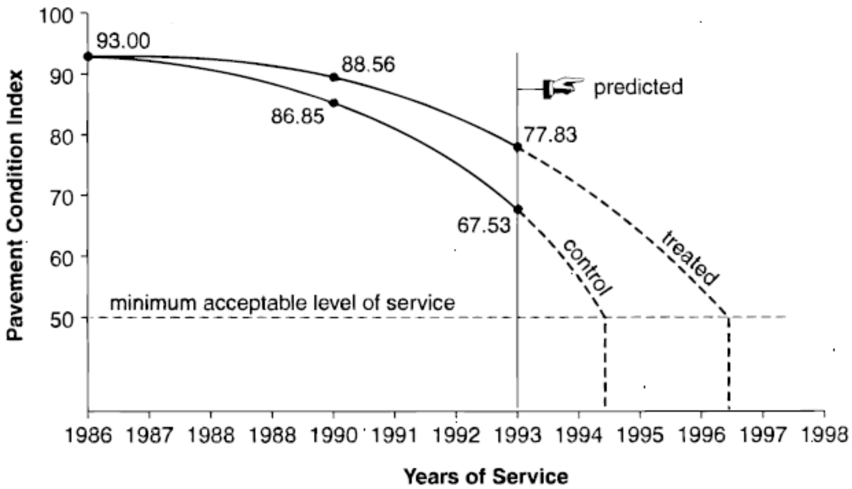


Figure 3 Service life extension illustration (from Ponniah and Kennepohl, 1996).

5.3.3 Quality Control

Maintaining good quality control during installation of crack sealant is very important, as improper cleaning or installation of the crack sealant can decrease the service life of the sealant. Crack sealing performance is directly related to the care and detail taken during the cleaning and installation of sealants (Decker, 2014). A sample checklist from FHWA (2001) is provided in Appendix A. Main topics covered in this checklist include:

- surface preparation,
- weather requirements,
- routing,
- crack cleaning
- hot air blasting
- sealant application, and
- common problems and solutions.

5.4 Evaluation Methodologies

Monitoring the performance of crack sealing is important to help ensure the effectiveness of the treatment strategies. It is generally recommended that field evaluations be conducted when the sealant is at its greatest extension, or near the approximate anniversary of the date of installation. A representative length of roadway, approximately 500 feet in length, should be visually evaluated in both lanes. Sand, rocks and debris must be removed from the test area before any readings are taken. Data that should be collected include water infiltration from adhesion and/or cohesion distresses, the severity of debris or stone retention, spalling of the edges of the crack, crack movement, crack spacing a photo log, tracking, pullouts, annual average daily traffic, deicing chemicals used, and weather data (NTPEP, 2016). This information can be used to determine which sections to retreat first or whether to discontinue treatment if a resurfacing operation is scheduled. This information can also be used to evaluate the cost benefit of crack sealing and the effectiveness of certain materials or techniques.

A visual system based on the Sealant Condition Number (*SCN*) is outlined in AASHTO NTPEP (2016) to evaluate sealant performance. Evaluations are centered on two main distresses: water infiltration, and stone and debris retention. *SCN* is calculated using Equation **1**.

$$SCN = 1(L) + 2(M) + 3(H)$$ ***Equation 1***

where L = the number of low severity sealant conditions, M = the number of medium severity sealant conditions and H = the number of high severity sealant conditions. A *SCN* of 0 is the best possible condition while a *SCN* of 6 is the worst possible rating. Water infiltration or crack sealant failure is determined by Equation **2**.

$$\%L = \frac{L_f}{L_{tot}} * 100$$ ***Equation 2***

where $\%L$ = percent length of the crack allowing water infiltration due to adhesion or cohesion loss, L_f = total length of the crack sealant field evaluation section allowing the infiltration of water, and L_{tot} = total length of the crack sealant field evaluation section. In general, the severity of water infiltration as outlined by AASHTO NTPEP (2009) is outlined as follows:

- No water infiltration: $0 < \%L \leq 1$
- Low severity water infiltration: $1 < \%L \leq 10$
- High severity water infiltration: $\%L > 30$

Stone or debris retention is rated as outlined:

- No debris retention – no stones or debris are stuck to the top of the sealant or embedded on the surface of the sealant/HMA interface.
- Low severity – occasional stones and/or debris are stuck to the top of the sealant, or debris embedded on the surface of the sealant/HMA interface.
- Medium severity – stones or debris are stuck to the sealant and some debris is deeply embedded in the sealant or material embedded between the sealant and the crack face but not entering the crack below the sealant.
- High severity – a large amount of stones is stuck to and deeply embedded in the sealant or filling the crack, or a considerable amount of debris is embedded between the sealant and the crack face and entering the crack below the sealant.

Other items of interest during these evaluations include full depth adhesion loss, full depth cohesion loss, complete pullout of material, secondary cracking or spalls extending below treatment material to crack, and potholes.

The National Transportation Product Evaluation Program (NTPEP) published a user guide (NTPEP, 2012) to help interpret and use data from the NTPEP evaluation program, which evaluated sealant products that were installed using a variety of nationally accepted standard procedures. According to this guide, the limits for the water infiltration criterion vary. As summarized in that guide, Canadian limits in Manitoba were 7% for the first year and 10% for the second year (Fer and Kavanagh, 2006). A separate study conducted by the National Research Council of Canada (Masson et al., 2003) suggested ranges based on location (Vancouver, Montréal and Ottawa) and number of years in service. The Federal Highway Administration defined service life as the time to reach 25 percent failure (Smith and Romine, 1999). The NTPEP guideline also suggests that evaluations are conducted annually during mid-winter or early spring to determine effectiveness. Measurement of the following failure types should be made to evaluate the performance of crack sealants: full-depth adhesion loss, full-depth cohesion loss, complete pullout of material, spalls or secondary crack extensions, and potholes. An evaluation period of 2 to 3 years is generally sufficient to accurately assess material performance (NTPEP, 2016).

5.5 Summary of Literature Review

The use of hot-pour materials with high elastic properties at low temperatures should yield approximately 3 to 5 years of life from the sealants themselves. Although there are mixed results regarding the benefit of crack sealing on the life of the pavement, benefits are more pronounced in areas with sensitive subsoils. Pavement life extensions of up to approximately 2 years have been observed. The following items are listed for consideration based on the information collected from the literature to improve the quality and effect of crack sealant materials within South Dakota.

- Consider utilizing wider routs for wider cracks or cracks with larger movements to help reduce stress concentrations at the edges by transfer of stresses to the bottom of the rout.
- Continue to use compressed air as the standard for cleaning cracks, but when the heat lance is used, consider limiting temperatures to keep from damaging the pavement.
- Consider reducing the humidity level requirement to minimize the effect moisture has on how well the sealant adheres to the crack sidewall.
- Consider adding modified bending-beam rheometer and direct tension tests to evaluate good crack sealing materials.

6.0 INTERVIEWS

Engineers, construction managers, maintenance personnel, and contractors within South Dakota have extensive experience from decades of applying and evaluating crack sealants within the state. Telephone interviews were conducted with nine individuals to learn as much as possible from those involved with crack sealing of pavements in SDDOT.

6.1 Interview Questions

A list of questions was put together prior to conducting the interviews. Not all questions were asked of every interviewee, but were used simply as a guide during the conversation. The various topics discussed and the associated questions are included in Appendix B.

6.2 Summary of Interviews

Interviews were made with nine individuals, eight of which worked for SDDOT and one contractor. Those interviewed during this project were well acquainted with crack sealing of pavements, ranging from about 8 to 18 years of experience. Everyone was able to articulate their individual experiences with crack sealing well and had a good idea of the installation process and associated material requirements. General information from the interviews is synthesized below.

Crack sealing in South Dakota consists of rout and seal efforts done by contractors and in-house efforts done by maintenance crews. Contracted crack sealing follows the specifications and construction guidelines outlined in the project requirements, while crack sealing by maintenance personnel tends to vary from region to region based on engineering judgment and local experience. Contracted crack sealing is the first maintenance effort used to help prolong the life of new or recently rehabilitated pavements. This initial crack sealing is typically done on pavements that are one to two years old. Generally, in year three (but always after crack sealing) the new pavement surface is chip sealed. Chip seals are typically done on a seven-year cycle. After chip sealing, maintenance crews conduct follow-up crack sealing and filling operations on any new cracks or on cracks where the sealant has failed. This follow-up maintenance crack sealing is almost always done by SDDOT maintenance crews, usually in late winter (February/March timeframe). Maintenance crews typically use hot pour crack sealants that are preapproved or a crumb-rubber based material. Follow-up crack sealing operations by maintenance crews usually extend through the life of the overlay. This cycle repeats itself once a new overlay is constructed or major improvement is made. Maintenance crack sealing does not typically re-rout cracks but simply fills in the crack using a band-aid approach. At times, a hot-pour crumb-rubber product is used for the maintenance crack sealing. This product is typically installed when the crack is fully open (February/March timeframe) so that no additional tensile forces are placed on the material, only compressive forces. This helps keep the seal on the crack as the crack narrows under higher temperatures. If narrowing of the crack pushes the material up so that it is distended above the surface of the roads, it can, at times be tracked by vehicles in the wheel path; however, rarely does this material pullout of the crack. Because maintenance sealing operations are done during winter, there tend to be more issues associated with moisture in the crack due to thawing or condensation. Some use a heat lance, but thawing the roadway may not solve water issues.

During contracted crack sealing, cracks are routed to ¾ in. by ¾ in., blown free of dust and moisture using compressed air, and filled using a wand. A squeegee is used to level the sealant which creates an overband of about 1 to 3 in. Toilet paper used as a blotter material. Care needs to be taken when blowing out cracks on pavements with older chip seals as the compressed air can lift the chip seal from the original pavement surface. If a hot lance is used, care must also be taken not to overheat the pavement as it will break down the asphalt and make it more difficult for the crack sealant to adhere to the sidewalls of the crack. Material is sampled from the kettle through the wand for testing purposes. Using this method, the crack sealant is installed prior to the completion of the QA/QC testing. Contracted crack sealing is done in the spring or fall to avoid extreme hot and cold temperatures.

Most interviewed were generally familiar with the guidelines on how crack sealing should be performed by contractors, but there are differences in how various Regions manage maintenance crack sealing. Most agreed that selection and maintenance of the approved products list (APL) is important, and that there should be a robust process to determine which products are selected or delisted. There is no formal process at this time; however, an ad hoc evaluation method has been used based on test sections where one or more sealants are compared to a control. There is also a general feeling that the lab tests that were used in the past to evaluate the materials are not as good at predicting product performance. There hasn't been enough time to thoroughly evaluate more recent changes to South Dakota's specifications (namely, humidity, time of year).

Challenges associated with crack sealing in South Dakota were discussed during the interviews. The list below highlights the primary challenges discussed.

- Better education
  - Better education will provide a more consistent approach.
  - Better guidance will help understand good or bad performance.
  - Better guidance is needed to know how to appropriately penalize products that do not meet the specifications.
  - Further evaluation of discrepancies between various regions around South Dakota on how failures are characterized.
- Lab testing that better relates to performance
  - Ad hoc methods have been used in the past to determine whether to allow individual crack sealing products to be listed on the APL or delisted.
- Improve crack sealing performance
  - The perceived life of crack sealing varies greatly with some areas experiencing 1 to 2 years of life while others claimed up to 5 years of life.

- Because contracted crack sealing operations are obscured by chip seals within a year or so after they are installed, it is difficult to determine their life.
    - Crack sealing not able to withstand the expansion of the pavement, so there are many adhesion and cohesive failures, even within a year or two.
    - Early debonding of crack sealant in several cases.
    - Unsealed cracks do not perform well (secondary cracking, subsidence).
    - Determine whether there are issues with compatibility between certain types of stone (e.g., quartzite vs. granite) and crack sealant.
    - The age of the pavement should be taken into consideration.
    - Many conflicting variables make it difficult to determine what is causing some sealants to work better than others.
    - Mainly adhesion failures.
    - Areas sensitive to moisture intrusion tend to experience greater subsidence and secondary cracking.
    - Influence of pavement mix design should be taken into consideration.
    - Eastern part of the state tends to have more issues with crack sealant performance, and this may be due in part to the humidity and moisture.
    - Most thought it was reasonable to expect about 3 to 5 years of life out of contracted crack sealing.
    - There is no formal program at SDDOT to monitor the long-term field performance of crack sealing.
- Installation
    - Need a better inspection program to make sure that construction is done well.
    - Thawing during spring can bring water up from the ground which is difficult to deal with when crack sealing.

Overall, pavement preservation has changed the way engineering and maintenance personnel perceive the benefit of crack sealing pavements. More attention is being given to preventive maintenance applications and their effect on pavements. Many interviewees were not able to distinguish whether the performance of crack sealing is declining or whether they were simply paying less attention.

Detailed notes taken during the interviews are provided in Appendix B.

7.0 EVALUATION AND PAST FIELD PERFORMANCE

The general performance of several crack sealing installations was reviewed during a site visit by Eli Cuelho (project PI) in November 2016. Multiple sites were investigated on Highways 11, 13, 17, 38, 44 and 81 (general characteristics are listed in Table 9). A quick visual assessment of these installations was made and project details were discussed with Brian Vandam, SDDOT Transportation Specialist out of the Sioux Falls area office. Available documentation related to the construction and materials was collected and reviewed as part of this task. Weather during the site visits was unseasonably warm (high of 70°F) which made it difficult to evaluate the current performance of the sealants in a typical "cold" condition. Nevertheless, many of the issues documented by Mr. Vandam in years past helped highlight the issues associated with many of the installations.

Table 9: General information on highways evaluated

	Hwy. 11	Hwy. 13	Hwy. 17	Hwy. 38	Hwy. 44	Hwy. 81
Surface Type	4251†	4251†	4251†	4251†	4251†	4251†
Beginning MRM	90.87	107.99	42.05	350.04	395.82	94.73
End MRM	102.55	115.09	43.05	356.0	400.42	107.73
Last Year Resurfaced	2003	2011	1987	2012	2012	2010
Number of Lanes	2	2	2	2	2	2
Width (ft.)	26	24	24	24	24	34
ADT	2227	1381	3277	1665	958	1639
Crack Sealant	Beram 3060LM	W.R. Meadows #3405	Beram McAsphalt 195LM	Deery 101ELT	Beram McAsphalt 195LM	Crafco 522
Rout size (width x height)	¾" x ¾"	NP	¾" x ¾"	¾" x ¾"	⅝" x ⅝"	¾" x ¾"
Installation Date	6/7-6/13 2013	2013	6/27-6/28 2013	6/14-6/19 2013	6/25-6/26 2013	6/3-6/5 2013

† Bituminous asphalt surface greater than 1 in. thick
NP = information not provided

7.1 Crack sealant conditions

Mr. Vandam reviewed and documented the condition of the crack sealants shown in Table 9 during the winters of 2013 and 2014, six months after installation of the crack sealant at these locations. Photos were taken on Highways 11, 17, 38, 44 and 81 during the winter of 2013, and photos were taken on Highway 13 during the winter of 2014. Select photos are included in the discussion below to show the general condition of the cracks at these locations. The remaining photos taken by Mr. Vandam are in Appendix C. The following subsections, describe in more detail, the condition of the crack sealant at each of these locations based on personal interviews with, and information and photos from Mr. Vandam.

7.1.1 Highway 11; Beram 3060LM

Photos during the winter reveal full adhesion failures along the sidewalls of many of the sealed cracks. In some cases, the unsealed gap was greater than ¾ in. wide (MRM100, 102). In most of the cracks, the sealant did not seem to stretch at all as the gap widened with cooler temperatures. The asphalt in the area is approximately 10-12 years old. Based on personal conversations with Mr. Vandam, there were water issues during the installation process. Specifically, water was being held in the pore structure of the pavements and coming up from the bottom of the crack, making it difficult to dry them out prior to installation of the sealant. Part of this pavement was fog sealed in 2016. Subsidence of the cracked area was evident in many of the cracks. An example of this subsidence is shown in Figure 4.

Figure 4 Evidence of subsidence near the crack, Highway 11 – winter 2016.

7.1.2 Highway 13; W.R. Meadows #3405

This section of roadway has low traffic and low crack density. Photos taken during the winter of 2014 show relatively good performance (W.R. Meadows #3405), with some cracking along the edges of the reservoir evident in the chip seal (example in Figure 5). A small metal plate was placed over a portion of some of the cracks when the chip seal was installed to keep the chip seal off the sealed crack in that area (see Figure 6). Referring to Figure 6, the exposed crack sealant looked to be performing well with only light oxidation and surficial cracking along the edges of the reservoir. The site visit during winter 2016 showed slightly more distress in the exposed crack sealant, but overall seemed to be performing well (Figure 7).

7.1.3 Highway 17; Beram McAshpalt 195LM

Photos taken during winter of 2013 reveal multiple distresses in the crack sealant (Beram McAsphalt 195LM) prior to chip sealing the pavement surface. Adhesion failures seem to be the predominant distress, although there is also evidence of cohesive failure in the sealant surface (example shown in Figure 8). The photos also indicate that there was extensive movement of the pavement at these locations (more than a half inch in some locations). This site was not visited during winter 2016.

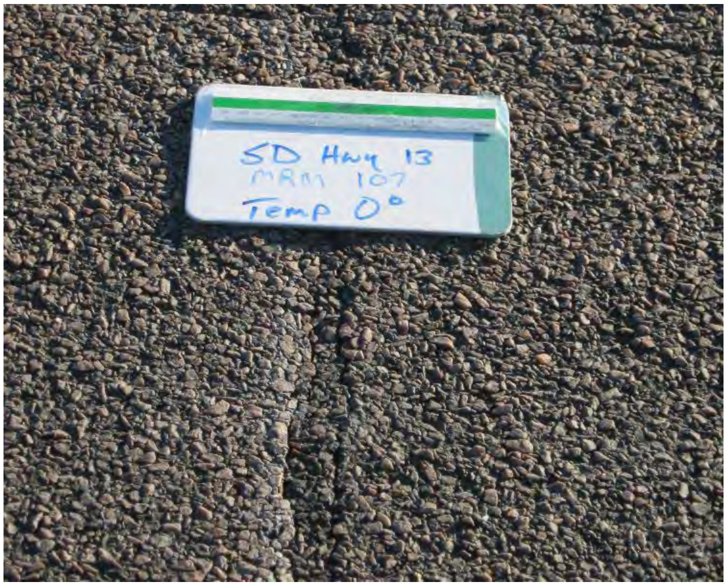


Figure 5 Crack sealant on Highway 13, MRM 107 – winter 2014.

Figure 6 Exposed crack sealant on Highway 13, MRM 110 – winter 2014.

7.1.4 Highway 38; Deery 101 ELT

The Deery 101 ELT crack sealant on Highway 38 was performing fair when evaluated in 2013. Photos taken prior to chip sealing show some secondary cracking and surface oxidation. An example of this is shown in Figure 9. Secondary cracking like the ones shown in Figure 10 may be due to high stress in the crack sealant as the crack widens during colder temperatures. If the bond between the crack sealant and the sidewalls of the reservoir are stronger than the tensile strength of the asphalt, then the asphalt will crack adjacent to the reservoir causing secondary cracking. A site visit during winter 2016 after chip sealing showed cracking in many areas through the chip seal. It is unknown whether the cracking extends through the underlying crack sealant. SDDOT maintenance personnel had recently re-sealed some of the cracks in this area.

Figure 7 Exposed crack sealant on HWY 13, MRM 110 – winter 2016

Figure 8 Crack sealant on Highway 17, MRM 47.48 – winter 2013.

7.1.5 <u>Highway 44; Beram McAsphalt 195LM</u>

An evaluation of the crack sealant was done during winter 2013 prior to chip sealing the highway. Photos taken during that evaluation show extensive adhesion failures along the sidewalls of the crack which can be either to secondary cracking of the pavement or adhesion failures. Secondary cracking is likely due to high stresses in sealant during winter, as described above. There are also significant cohesive failures on the surface of the sealant. An example of the types of failures are shown in Figure 11.

Figure 9: Crack sealant on Highway 38, MRM 361 – winter 2013.

Figure 10: Crack sealant on Highway 38, post chip seal – winter 2016.

7.1.6 Highway 81; Crafco 522

Failures in Crafco 522 at this location indicate recession of the sealant in the reservoir (refer to Figure 12). There is also a lot of adhesive failures at this location that extend into the crack sealant and not just in the chip seal. Many areas experienced double adhesion failures where the crack sealant failed along both sides of the reservoir. A representative photo of the typical distresses at this location is shown in Figure 13.

Figure 11: Crack sealant on Highway 44, MRM 401 – winter 2013.

Figure 12 Recession of the crack reservoir on Highway 81, MRM 98 – winter 2013.

7.2 Summary

The performance of many of the crack sealants at the locations reviewed on Highways 11, 13, 17, 38, 44 and 81 in South Dakota was poor, based on a review in 2013 by Mr. Brian Vandam of SDDOT. A subsequent visit by WTI staff to many of these sites in late 2016 revealed similar conclusions but to a lesser extent due to unseasonably warm temperatures last fall. The majority of the failures were adhesion failures with surficial cracking of the sealant and intermittent secondary cracking. The performance as documented in winter 2013, only six months after installation of the majority of the crack sealants reviewed, was poor. The results of these evaluations are summarized in Table 10.

Figure 13 Typical distresses of the crack sealant on Highway 81, MRM 103 – winter 2013.

One noteworthy aspect of the crack sealing process is the sequence of events that typically occurs for pavement maintenance activities and how this may possibly affect the performance of the crack sealant. After a pavement is replaced or rehabilitated (e.g., overlay), it is allowed to rest for about a year. During the winter, it will likely experience cracking as the pavement contracts in the colder temperature. Cracks that form during the first winter are typically addressed the following spring or fall through contracted crack sealing efforts. If the first contracted crack sealing after rehab was done in the spring, then it is likely to be chip sealed that following summer (about one year after paving), while crack sealing efforts that occur in the fall would be chip sealed the next summer (about two years after paving). Any new cracks that form after the chip seal is installed and any subsequent failures in the first chip seal is typically addressed internally by SDDOT staff versus contracted crack sealing.

Chip sealing after crack sealing may pose a mechanical challenge for the crack sealant in that the chip layer adds a stiff 'crust' across the top of the crack. This layer is essentially inflexible when compared to the crack sealant. Therefore, when strain is experienced at the crack (due to fluctuations in pavement temperature), the chip seal 'crust' is unable to stretch and will crack, usually along one of the edges of the reservoir. The difference in stiffness between the chip seal and the crack sealant in many cases causes the crack sealant to pull away from the edges of the crack reservoir (adhesion failure) or within the sealant (cohesion failure) thereby allowing water to infiltrate into the crack.

Table 10: Summary of performance evaluations during site visits

Highway	Sealant	General Performance	Potential Issues Affecting Performance
11	Beram 3060LM	• full adhesion failures • subsidence	• 10-12 year old asphalt • water issues • poor subgrade • stiff sealant • poor bonding
13	W.R. Meadows #3405	• performing relatively well	• low traffic • low crack density
17	Beram McAsphalt 195LM	• predominantly adhesion failures • cohesion failures evident	• extensive joint movement • poor bonding • chip seal • stiff sealant
38	Deery 101ELT	• performing fair • extensive adhesion failures • secondary cracking,	• chip seal • poor bonding • low tensile strength in asphalt • missed cracks when routing
44	Beram McAsphalt 195LM	• extensive adhesion • significant cohesion failures prior to chip seal • secondary cracking	• chip seal • Poor bonding • low tensile strength in asphalt • missed cracks when routing • narrow rout width
81	Crafco 522	• adhesion failures • double adhesion failures • recession of the sealant	• chip seal • stiff sealant • poor bonding

8.0 CRACK SEALANT INSTALLATION

8.1 Test Site Locations

The location of the test sites selected by SDDOT and researchers are on US highway 14, beginning approximately 2 miles west of Highmore, SD (Figure 14) and on SD Hwy 50, approximately 3 miles west of Yankton, SD (Figure 15). Both test sites were asphalt overlays constructed in 2015 and were rated as being in excellent condition by SDDOT field engineers present during crack sealant installations. The test sites were broken into eight test sections, each with a different crack sealant material installed as shown in Figure 16. The crack sealant manufacturer, product name, and location at each test site is shown in Table 11. The mileage reference markers (MRMs) for the beginning and end of the eight crack sealant test sections for both the Highmore and Yankton test sites are shown in Figure 17.

Figure 14 Location and mileage reference marker (MRM) for Highmore test site

Figure 15 Location and mileage reference marker (MRM) for Yankton test site

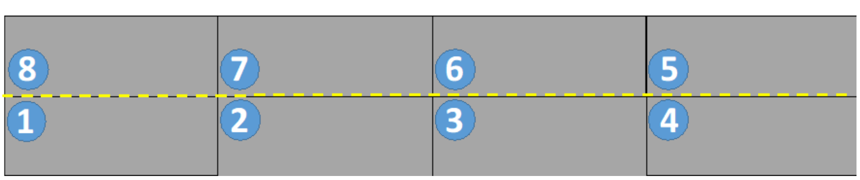


Figure 16 Crack sealant test regions

Table 11 Crack sealant manufacturer, product, and location shown in Figure 16

Manufacturer	Product	Location Highmore	Yankton
Crafco, Inc.	Deery 101SD	5	6
Crafco, Inc.	Deery 101 ELT	7	3
Crafco, Inc.	Roadsaver 231SD	6	1
Crafco, Inc.	Roadsaver 522	3	4
Right Pointe Co.	Mod 4 3405	1	5
W.R. Meadows, Inc.	3405 M	4	8
Maxwell Products, Inc.	Elastoflex 72	2	7
McAsphalt Industries	MacSeal 6690	8	2

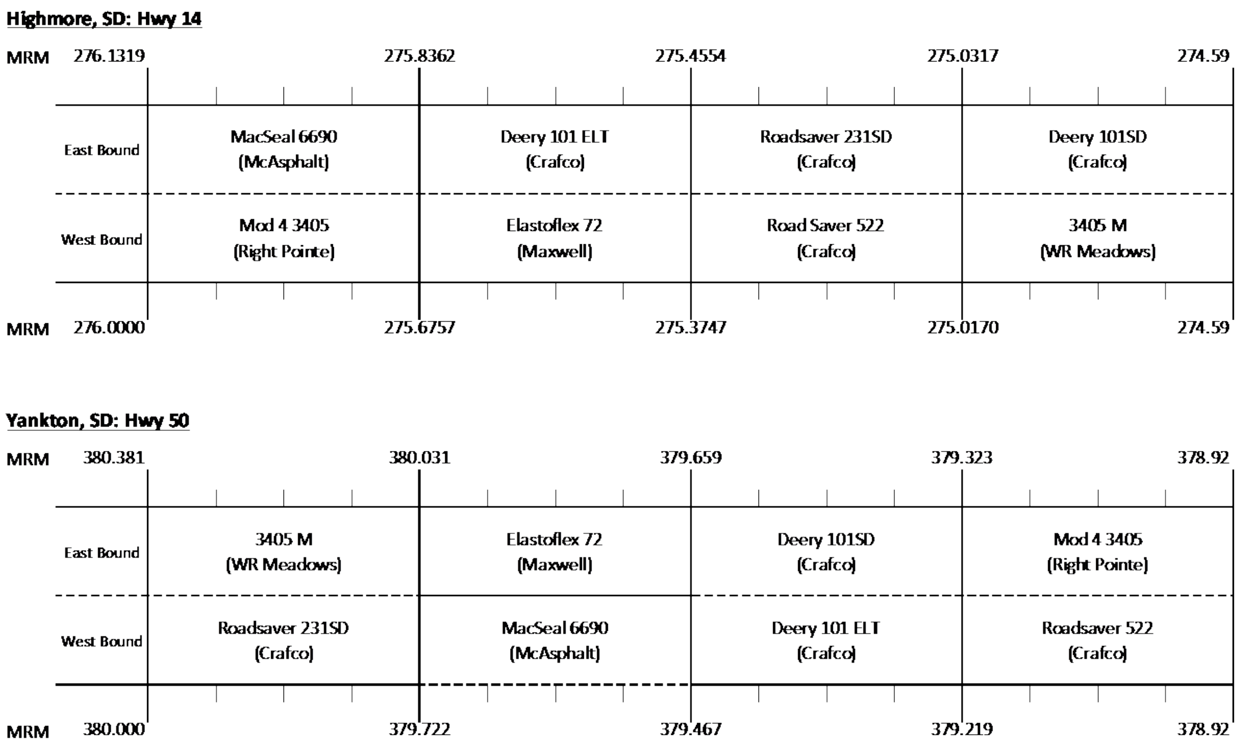


Figure 17 MRM locations of crack sealant products (not to scale)

8.2 Construction

Asphalt Surface Technologies Corp. (ASTECH), Saint Joseph, MN, performed all crack routing, cleaning, and sealant installations for both the Highmore and Yankton sites on 9/6/2017 and 9/7/2017, respectively. Approximately 500 to 700 lbs. of each sealant (Figure 17) were installed at each test section. The installations at both sites were performed in a continuous manner, beginning with Test Section 1 (Figure 16), progressing to Test Section 2, through Test Section 8 using a single kettle for each test section. Two kettles were used by ASTECH so that material could be heated while a different crack sealant material was placed with the other kettle which are shown in Figure 18. Crafco Co, Inc. provided their own kettle that distributes material on demand (no recirculation) for the installation of Crafco products and is shown in Figure 19.

Figure 18 Kettles used by Asphalt Technologies Corp. for heating and installing crack sealants

Figure 19 Kettle used for Crafco, Inc. crack sealant products

All crack sealants were heated to the manufacturer's recommended installation temperature and were installed over similar time durations. When the kettle and wand were empty, the second kettle with a different crack sealant material was then used to continue the crack sealant installation.

8.3 Data Collection

Construction information collected during the sealant installation included environmental conditions, pavement conditions, and the overall crack sealing process. The datasheet used to collect document some of this information included in Appendix D.

Installing the crack sealants at the Highmore and Yankton location lasted from approximately 9:00am until 5:00pm at each location. Ambient temperatures ranged from 42° to 68°F at Highmore and 53° to 73°F at Yankton. Skies were clear and road surfaces were dry before and during crack sealant installations. Routed dimensions of the crack sealants were approximately ¾-in. wide by ¾-in. deep and were cleaned using compressed air.

Two material samples were taken during the crack sealant installations at approximately the half-way location of each test site. Approximately 5 lbs. of material were collected in a Teflon/silicone lined cardboard box for required material testing conducted by SDDOT. A larger sample was collected in a steel bucket for possible additional material testing. The material samples collected are shown in Figure 20. Temperatures of the sealant material were measured using a non-contact infrared thermometer. Temperatures at the wand while filling the sample containers and pavement temperatures for each test section were recorded and are shown in Table 12.

Figure 20 Material samples taken at approximately midpoint of test sections

To estimate the average crack spacing, the total length of each test section was calculated using the starting and ending MRMs then divided by the total number of cracks sealed. Average crack spacings calculated for the two test sites is shown in Table 13. The smaller average crack spacings estimated for the Yankton site are likely due to the concrete pavement beneath the bituminous overlay and are reflected from the concrete joints below.

Table 12 Crack sealant installation data

	Product temperature @ wand (deg. F)		Road surface temperature (deg. F)	
Product	Highmore	Yankton	Highmore	Yankton
Deery 101SD	370	400	112	113
Deery 101 ELT	370	385	111	74
Roadsaver 231SD	380	380	119	71
Roadsaver 522	390	365	85	87
Mod 4 3405	380	350	61	114
3405 M	385	370	94	105
Elastoflex 72	350	380	71	113
MacSeal 6690	365	380	115	74

Table 13 Test section length, number of cracks, and average crack spacing

	Highmore			Yankton		
Product	Length (ft)	No. of cracks	Average spacing (ft)	Length (ft)	No. of cracks	Average spacing (ft)
Deery 101SD	2176	63	35	1774	63	28
Deery 101ELT	2016	70	29	1309	73	18
Roadsaver 231SD	2246	59	38	1468	64	23
Roadsaver 522	1890	61	31	1595	87	18
Mod 4 3405	1693	58	29	2144	62	35
3405 M	2108	72	29	1848	101	18
Elastoflex 72	1595	66	24	1964	56	35
MacSeal 6690	1550	58	27	1346	62	22

The final measurement made at each crack sealant test section included the distance between two bituminous pavement nails, referred to as ‘pins’, installed on either side of the sealed cracks near the center of the test section. The measurements provide an estimate of the pavement contraction or expansion during the summer and winter inspections. The MRMs of the pins were recorded using SDDOT’s Microdynamics DOT-Z1 Pro distance measuring instrument. A picture of the pins is shown in Figure 21 and the MRM locations for the test sections at both test sites is shown in Figure 22.

Figure 21 Picture of bituminous nails

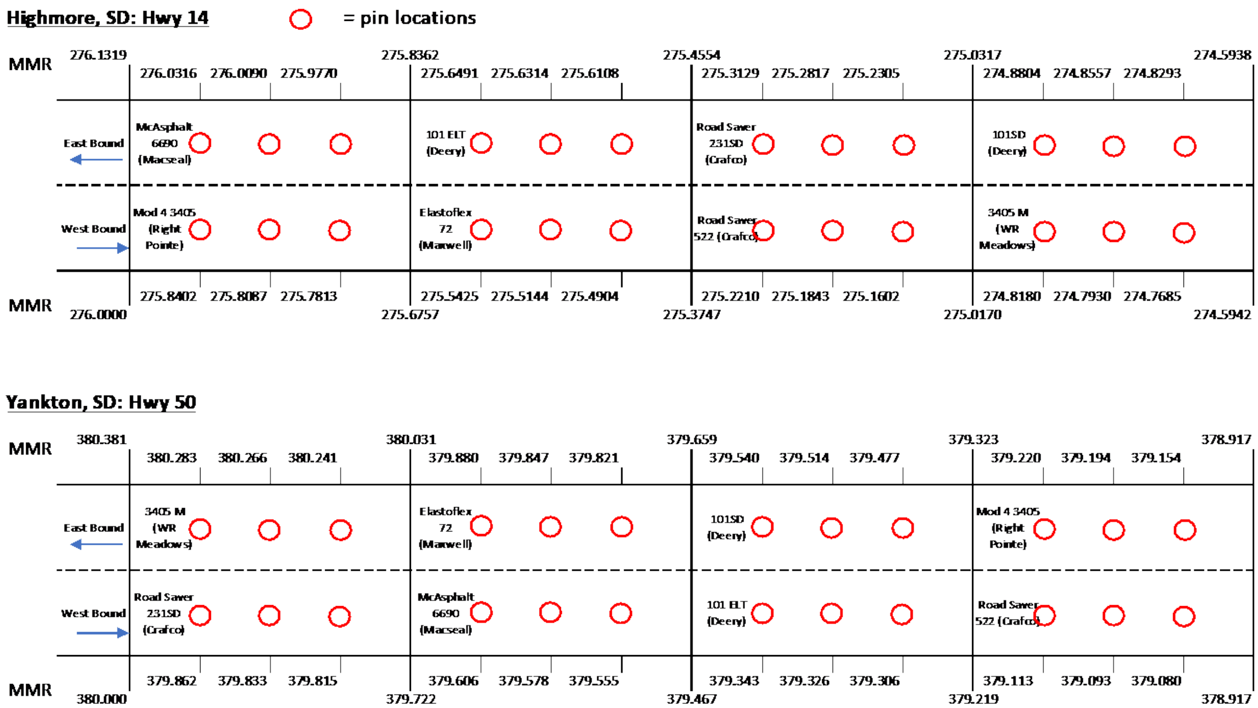


Figure 22 MRM locations of bituminous nails (red circles) used to measure pavement contraction and expansion

9.0 FIELD PERFORMANCE EVALUATION

9.1 Inspections and Performance Data

To evaluate the field performance of the eight different crack sealant materials at the Highmore and Yankton test sites, four site inspections were completed. Two inspections were made in the winter to capture the sealant performance during maximum cold-temperature pavement contraction. Two inspections were also made during the summer time during high ambient temperatures and maximum pavement contractions. The dates, time, and weather conditions for the installation and site visits is shown in Table 14. The timing of SDDOT chip seal operations is also shown relative to the site visits. Data collected during each site visit included pavement temperatures, measurements between the bituminous nails (Figure 22), and photographs along the lengths of selected cracks for each sealant material.

Table 14 Inspection visit dates time, and ambient temperatures

			Temperature			
			Air		Pavement	
Site Visit	Date	Time	Low	High	Low	High
Highmore installation	9/6/2017	9:00am - 5:00pm	42°F	68°F	61°F	119°F
Yankton installation	9/7/2017	9:00am - 5:00pm	53°F	73°F	71°F	114°F
Highmore 1	2/10/2018	9:30am - 1:00pm	-10°F	-5°F	-15°F	16°F
Yankton 1	2/11/2018	9:00am - 12:00pm	5°F	11°F	-14°F	-2°F
Highmore 2	6/16/2018	10:30am - 1:00pm	78°F	78°F	105°F	116°F
Yankton 2	6/15/2018	1:40pm - 5:20pm	93°F	96°F	113°F	127°F
Chip seal						
Highmore 3	3/21/2019	8:45am - 12:00pm	27°F	36°F	21°F	38°F
Yankton 3	3/22/2019	8:30am - 11:45am	32°F	39°F	35°F	51°F
Highmore 4	8/18/2019	10:00am - 12:00pm	53°F	60°F	79°F	98°F
Yankton 4	8/17/2019	11:00am - 2:20pm	75°F	83°F	91°F	126°F

9.1.1 Pavement Temperatures

Pavement surface temperatures were measured with a non-contact infrared thermometer at the location of each crack sealant material. A representative plot showing the variation of pavement temperatures during the installation and site visits is shown in Figure 23. The surface temperature of the pavement increases as the ambient air temperature and sunshine exposure also increases.

9.1.2 Pavement expansion and contraction

The average measurements between the bituminous nails or 'pins' for each sealant material is shown in Figure 24. The measurements made on 9/6/17 and 9/7/17 were done the same day the sealants were installed and are offset to obtain an initial zero reference. The highway test sections were chip-sealed after the second site visit and subsequent measurements were not available. Positive values recorded during the first winter inspection on 2/10/18 and 2/11/18 represent contraction of the pavement (larger distance between pins) due to the colder ambient temperature relative to their installation. The summer measurements made on 6/15/18 and 6/16/18 represents an expansion of the pavement (smaller distance between pins). Negative values indicate the initial pin measurement during installation was larger than summer inspection measurement. Measurements made for the three pin locations (Figure 22) for the crack sealant materials at the two test sites are shown in Table 15.

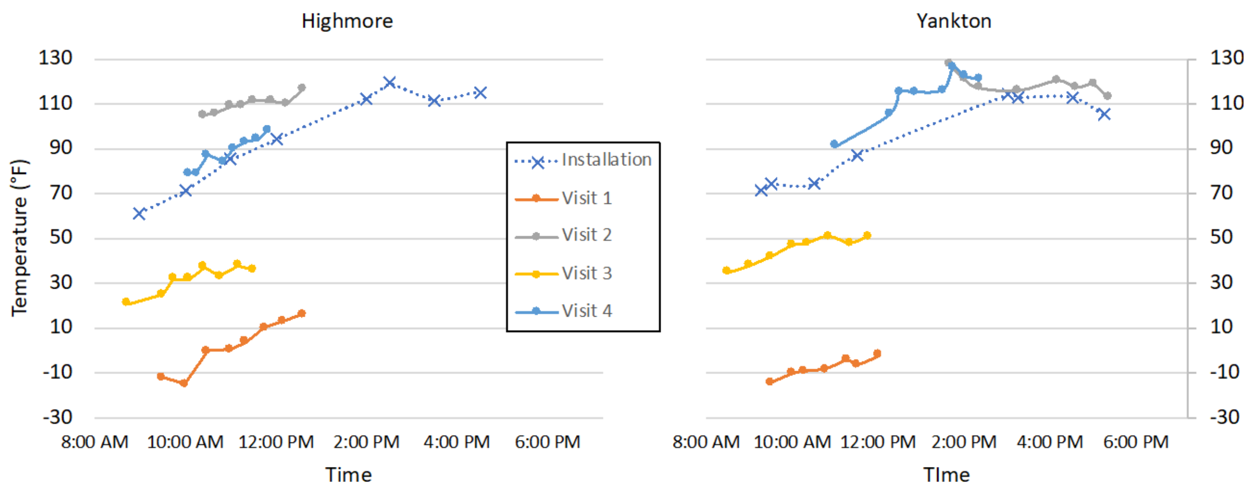


Figure 23 Measured pavement temperatures at Yankton and Highmore test sites

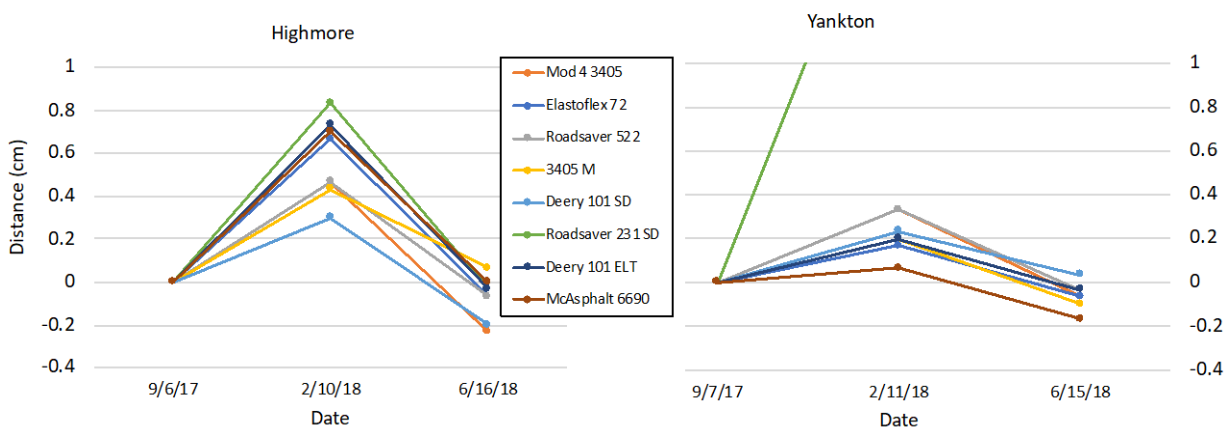


Figure 24 Bituminous nail measurements for Highmore and Yankton sites.

Table 15 Estimated pavement expansion/contraction measurements, cm

	Highmore								Yankton							
	2/10/18				6/16/18				2/11/18				6/15/18			
Product	1	2	3	Avg.	1	2	3	Avg.	1	2	3	Avg.	1	2	3	Avg.
Deery 101SD	0.2	0.3	0.4	0.30	-0.1	-0.4	-0.1	-0.20	0.2	0.4	0.1	0.23	-0.1	0.2	0	0.03
Deery 101ELT	1.3	0.6	0.3	0.73	0.1	-0.1	-0.1	-0.03	0.3	0.2	0.1	0.20	-0.1	0	0	-0.03
Roadsaver 231SD	1.4	0.2	0.9	0.83	0.1	-0.2	0	-0.03	0.4	3.2	2.6	2.1	0.3	2.7	2.0	1.7
Roadsaver 522	0.9	0.3	0.2	0.47	-0.1	-0.1	0	-0.07	0.4	0.3	0.3	0.33	0.1	-0.1	-0.1	-0.03
Mod 4 3405	0.4	0.3	0.7	0.47	-0.2	-0.2	-0.3	-0.23	0.2	0.4	0.4	0.33	-0.1	0	-0.1	-0.07
3405 M	0.3	0.5	0.5	0.43	0.1	0.1	0	0.07	0.3	0.2	0.1	0.20	0	-0.1	-0.2	-0.10
Elastoflex 72	0.8	0.9	0.3	0.67	-0.1	0	-0.1	-0.07	0.2	0.2	0.1	0.17	-0.1	-0.1	0	-0.07
MacSeal 6690	0.9	0.6	0.6	0.70	-0.1	0.1	0	0	0.2	-0.1	0.1	0.07	-0.1	-0.2	-0.2	-0.17

Outlying measurements were recorded for the 2nd and 3rd pin locations for the Roadsaver 231 SD product at the Yankton (green line in Figure 24). These values could be the result of incorrect initial measurements because of the quick readings that were required between vehicle traffic. The winter and summer measurements could have also been compromised from snow-plow contact with the pins.

The average contraction and expansion measurements from the initial September, 2017 measurements for the Highmore test site was 0.58 cm and -0.07 cm, respectively. For the Yankton site, excluding the outlying Roadsaver 231SD measurements, the average contraction and expansion measurements were 0.24 cm and -0.02 cm, respectively. The maximum pavement movement between winter and summer conditions can be estimated by subtracting the summer expansion from the winter contraction. This calculation results in estimated maximum pavement movement of 0.9 cm (0.35 in.) and 0.4 cm (0.16 in.) at the Highmore and Yankton sites, respectively. Larger values measured at the Highmore site can be partially attributed to the larger average crack spacings compared with the Yankton site (Table 13) and generally colder winter temperatures.

The pin measurements were collected to approximately quantify the magnitude of pavement expansion and contraction at consistent crack locations for each material. The estimated maximum pavement contraction corresponds to a crack sealant extension of 47% at the Highmore site and 21% at the Yankton location for a 3/4 in. wide joint. These extensions are well within ASTM D6690, Type IV crack sealant requirements, where materials must meet a 200% extension at -20°F.

9.2 Observed Distress During Winter and Summer Inspections

9.2.1 <u>Types of Distress</u>

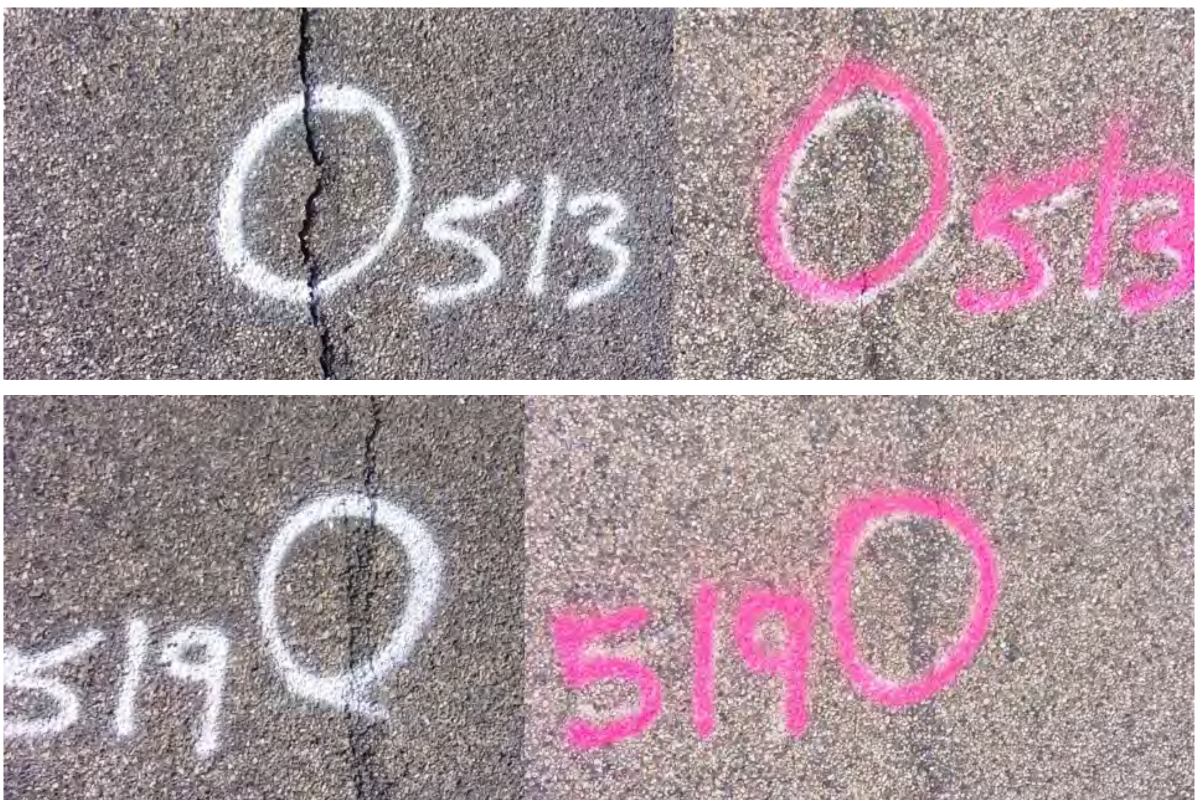
Distresses can be broadly classified into primary and secondary classes. Secondary distresses indicate degradation that may possibly lead to primary distresses in the future and most commonly include weathering, wear, bubbling, and stone or debris intrusion.

Primary distresses allow water to penetrate the pavement surface and most commonly include adhesion failures, cohesion failures, pullout, and secondary cracking. These distresses are quantitatively evaluated by measuring the length of distresses along each crack.

Adhesion and cohesion distresses are the two most common primary distresses experienced by crack sealants. Adhesion distresses are defined as the loss of bond between the crack sealant and the edge of a reservoir. Cohesion distresses are defined as any fracture within the sealant away from the crack edge. Pullout and secondary cracking distresses are caused by a combination of factors. Pullout is defined as the complete removal of sections of sealant from the pavement. Pullouts typically occur when a reservoir is used, in which case the pullout may be material and/or construction related; however, pullout distresses can also occur when band-aid or capped sealants stick to tires or are caught by snowplow blades. Secondary cracking is the formation of additional cracks adjacent to a sealed crack. These cracks can be caused by routing stresses, stiff sealants or settlement of the cracked area due to weakening of the subgrade and/or contamination of the base course.

9.2.2 Site Inspections

The winter inspections (Table 14) provided the most revealing signs of sealant distress due to the pavement contraction, requiring the sealant to span a larger routed reservoir width. Representative differences in observable distress for two crack locations during winter (3/21/19) and summer (8/18/19) inspections are shown in Figure 25. Additional comparison photographs for the two winter inspections and summer inspection for the same crack at each test section at both test sites are included in Appendix E.



(a) 3/21/2019 (b) 8/18/2019

Figure 25 Observed crack sealant condition during winter (a) and summer (b) inspections.

As shown in Figure 25 and Appendix E, sealant distress during the winter inspections are much more visible during the winter inspections, however confidently reporting these failures as adhesion, cohesion, or secondary cracking is not possible after the surface has been chip-sealed. An example of secondary cracking and cohesion failures observed during the winter inspection on 2/10/18 that become less apparent during the following year after chip-sealing is shown in Figure 26. The same areas of distress are identified next to the failure with a red line.

(a) 2/10/18 (b) 3/21/19

Figure 26 Sealant distress observed before (a) and after (b) chip sealing. Red lines drawn on both photographs represent the same sealant distress.

The more visible sealant distress observed during the winter inspections and the challenge of confidently identifying cohesion failures compared with secondary cracking led to the performance assessment methodology described in the following section.

9.3 Assessment Methodology

The methodology used to assess crack sealant performance focused on the two winter inspections because of the contracted pavements and the observable sealant distress. The selected cracks that were assessed for each test section and the observed distress conditions used to characterize the performance are described below.

9.3.1 Selected cracks

The MRM coordinates of the pin locations (Figure 22) were marked by SDDOT during installation and were located by SDDOT personnel and circled with paint prior to each inspection. These three full-width cracks were documented for the eight different sealant test sections at both test sites. To capture a larger segment of each test section, the third full-width crack from each side of the center pin in addition to the third full-width crack before the first and after the third pin location were selected to evaluate sealant performance. These seven crack locations are shown schematically in Figure 27 and provide a consistent number of cracks for each test section for both test sites. Their location in approximately the center portion of the test sections minimizes the potential for contamination between sealant products.

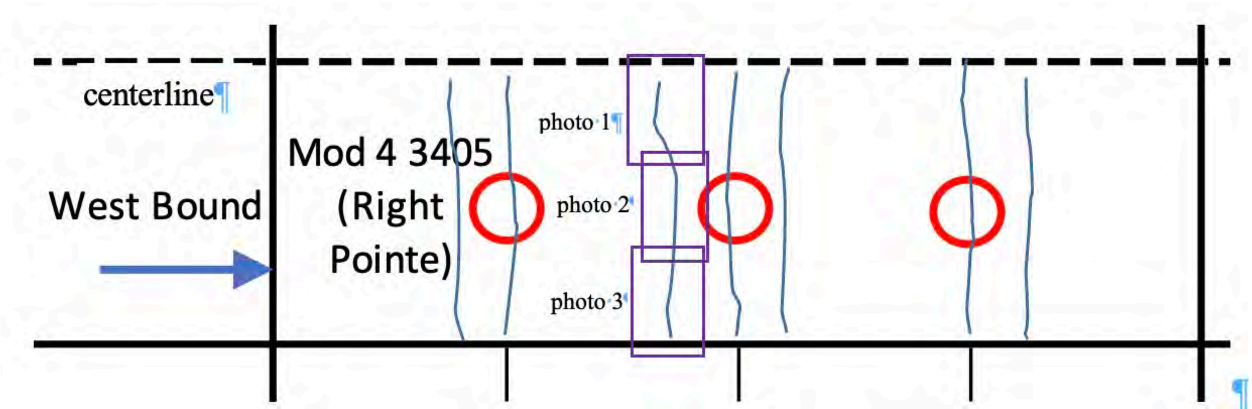


Figure 27 Approximate location of selected cracks for evaluation (not to scale)

Three photographs were taken for each of the seven cracks to document the full crack width (Figure 27). This documentation included 21 photographs (7 cracks per sealant x 3 photographs per crack) for each test section that were taken during the four site inspections. An example of the 21 assembled photographs are shown in Figure 28. These photographs were the primary data source used to assess the crack sealant performance.

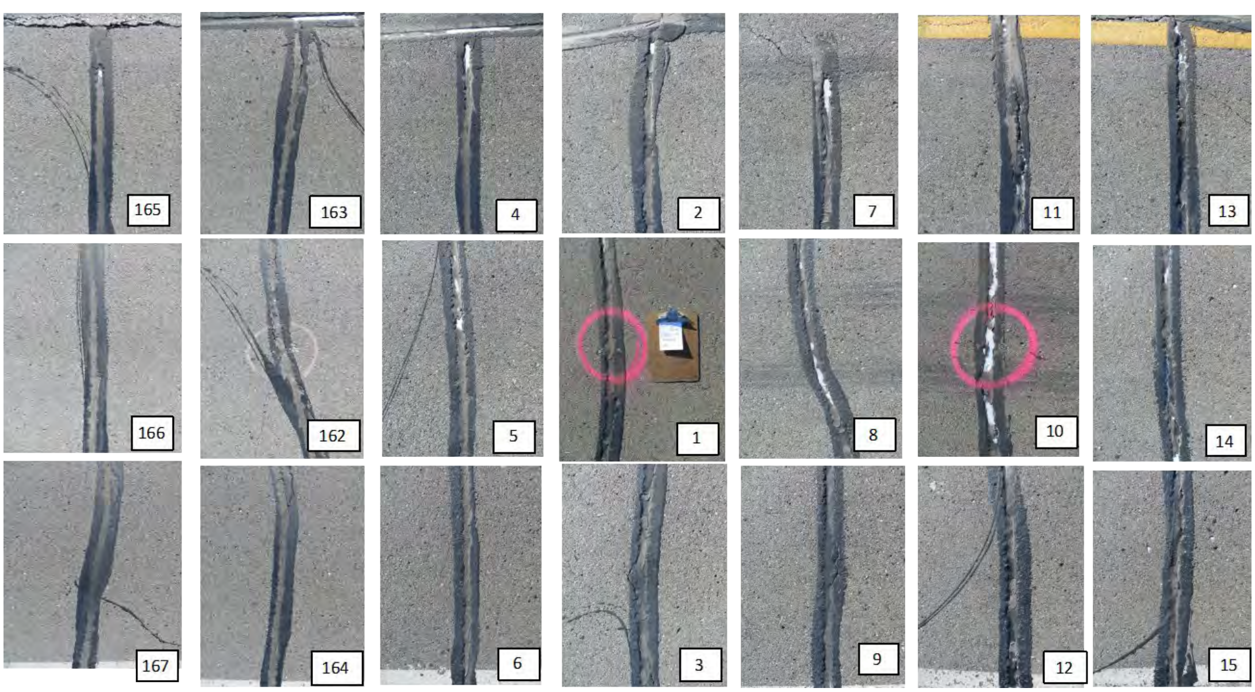


Figure 28 Representative photograph assembly of crack sealant test section used for evaluation.

Appendix F includes the 168 photos for each of the Highmore and Yankton test sites taken during the first winter inspection and Appendix G contains 168 photos taken during the second winter inspection. The pavement at the Yankton site for sealants Deery 101SD, Roadsaver 231SD, Elastoflex 72, and MacSeal 6690 were not chip sealed because of a future turn lane construction project.

The seven cracks represented by the 21 pictures for each test section (Figure 28) represent an approximate crack sealant assessment length of 84 ft (12ft lane width x 7 cracks) for each crack sealant and each photo captures approximately 48 in. (12ft/3 pictures). The total crack length and approximate photo length was used to quantify the approximate percentage of sealant distress observed during the site inspections.

9.3.2 Sealant distress conditions

Two different sealant assessment metrics are required for crack sealants inspected before and after chip sealing due to the visible features of the sealed crack.

9.3.2.1 Distress conditions without chip seal

Without a chip-sealed road surface, the full width of the routed joint and sealant are visible. For sealants inspected prior to chip sealing, three primary distress conditions were used to characterize the sealant performance; 1) no distress (ND), 2) secondary cracking, (SC), and 3) adhesion/cohesion failure (A/CF). These sealant conditions are described in Table 16 and examples shown in Figure 29. The images shown in Figure 29 were chosen to clearly illustrate the type of distress observed. Many of the observed distresses were less severe, and would be categorized as minor. Most of the adhesion/cohesion combined distress conditions observed were cohesion distress only, however this condition was combined with the few cases of adhesion distress, such as the case shown in Figure 30.

Table 16 Observed sealant condition and descriptions before chip seal

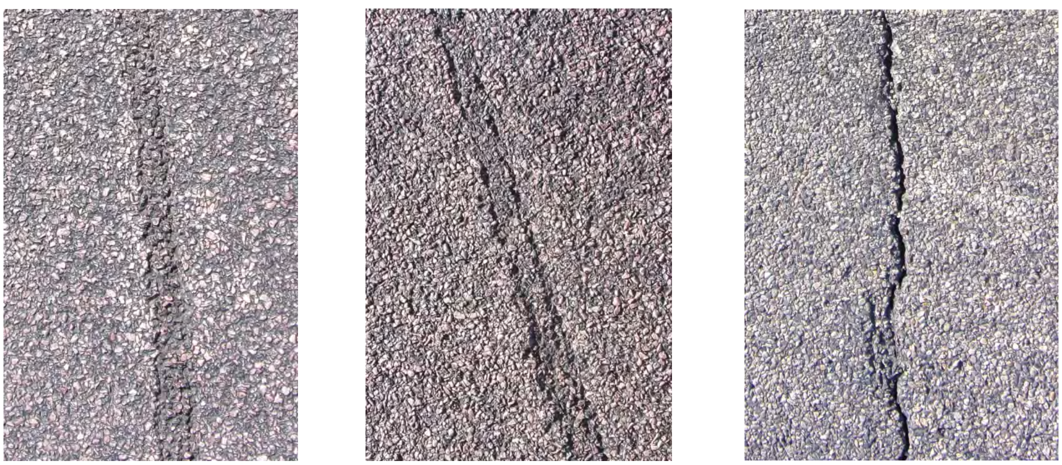
Observed Condition	Description
No distress (ND)	No sealant distress observed
Secondary cracking (SC)	Crack formation adjacent to sealed crack
Adhesion/Cohesion failure (A/CF)	Minor to major adhesion and/or cohesion failure within sealant

9.3.2.2 Distress conditions after chip seal

Because of the hidden crack sealant beneath the chip sealed surface, cohesion distress of the sealant and secondary cracking conditions were not used to assess the sealant performance. In addition to the no distress (ND), condition, minor cracking (MC) along the edges of the reservoir and adhesion failure (AF) conditions were used. These sealant conditions are described in Table 17 and representative examples are shown in Figure 30.

(a) no distress (ND) (b) secondary cracking (SC) (c) adhesion/cohesion failure (AF)

Figure 29 Observed sealant conditions before chip seal



(a) no distress (ND) (b) minor cracking (MC) (c) adhesion failure (AF)

Figure 30 Observed sealant conditions after chip seal

Table 17 Observed sealant condition and descriptions after chip seal

Observed Condition	Description
No distress (ND)	No sealant distress observed
Minor cracking (MC)	Minor cracking through the chip seal, with some sealant recession. Cracking doesn’t appear to reflect through to sealant.
Adhesion failure (AF)	Major crack along either side of the routed reservoir - reflects through to sealant.

9.3.3 Quantifying sealant distress

A close-up visual inspection of the 21 photographs, representing 84 ft of crack length, was completed to count the number of photos that included at least a 6 in. length of the distresses described in Table 16 and Table 17. This 6 in. minimum length for a sealant distress condition was used to estimate a minimum percentage of the 48 in. photographed crack length, which would be 12.5% (6in./48in.). If the entire photographed crack length included the observed condition, the maximum percentage would be 100% (48in./48 in.). This process can be extended over the 84 ft crack length (21 photos) using the number of pictures where a sealant condition was counted. For example, if the adhesion failure (AF) condition was counted in 9 of the 21 pictures, the minimum percentage of the 84 ft crack length with AF is estimated as 5.4% (9 x 6in./ 84ft / 12in./ft). Similarly, the maximum percentage is estimated as 42.9% (9 x 48in./84ft / 12in./ft). An average of these estimated minimum and maximum percentages is 24.2%. The average percentages of observed sealant distress in the 21 photos for each crack sealant was used to generalize the performance of the crack sealants with sealant distress. The no distress (ND) condition was only counted if the full 48 in. photographed crack length was observed to be free from distress.

9.4 Crack Sealant Performance Assessment

The crack sealant performance was assessed during the first and second winter inspections. The first winter inspection on 2/10/18 and 2/11/18 occurred only 5 months after the sealant installation and provided the only opportunity to evaluate the sealant material without the chip seal. The second winter inspection completed on 3/21/19 and 3/22/19, approximately 1.5 years after installation, provided insight into the performance of the sealant during the first winter after the pavements were chip sealed. These two inspection periods resulted in three assessments; 1) before chip seal, 2) after chip seal, and 3) shoulder crack sealants. The shoulder assessment was used at the Yankton test site because of that region's practice of not chip sealing the shoulders. This provided an opportunity to compare the sealant performance of the same crack with and without a chip sealed surface.

9.4.1 First winter inspection (before chip seal)

The total counted photographs with the no distress (ND) condition over the full photographed 48 in. crack length and percentage of total 84 ft length for both the Highmore and Yankton sites is shown in Table 18 for the first winter inspection. The counted photos for the secondary cracking (SC) and adhesion/cohesion failure (A/CF) conditions, the percentage ranges, and estimated average percentages are shown in Table 19. A bar graph showing the ND percent with the average SC and A/CF percentages is shown in Figure 31.

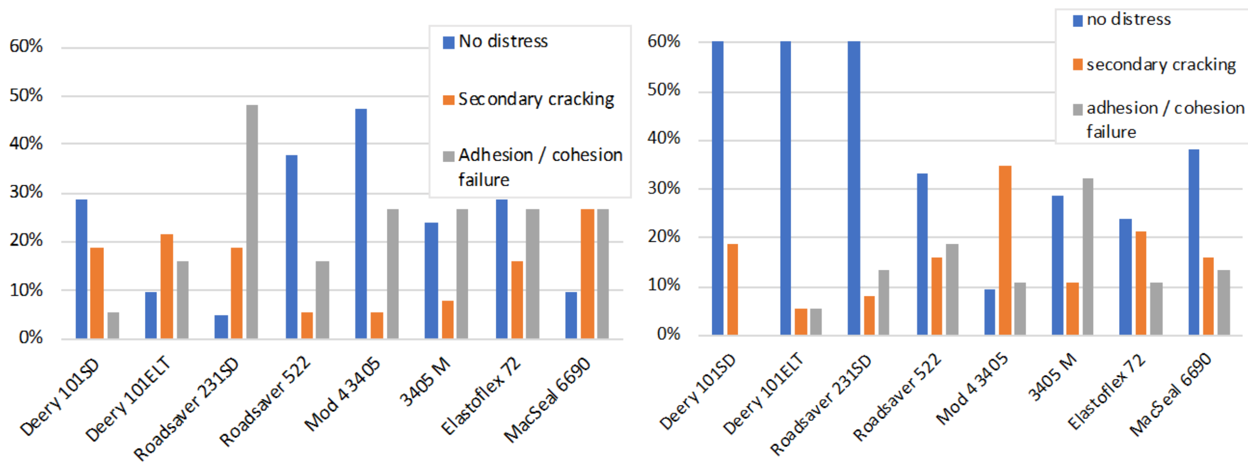
Table 18 Number of photographs with no distress and crack length percentage

	No distress (ND)			
Product	Highmore	%	Yankton	%
Deery 101SD	6	28.6	14	66.7
Deery 101ELT	2	9.5	14	66.7
Roadsaver 231SD	1	4.8	13	61.9
Roadsaver 522	8	38.1	7	33.3
Mod 4 3405	10	47.6	2	9.5
3405 M	5	23.8	6	28.6

Elastoflex 72	6	28.6	5	23.8
MacSeal 6690	2	9.5	8	38.1

Table 19 Approximate percentages of sealants with observed conditions

	Secondary Cracking (SC)						Adhesion/Cohesion Failure (A/CF)					
	Highmore			Yankton			Highmore			Yankton		
Product	No.	range (%)	Avg (%)	No.	range (%)	Avg (%)	No.	range (%)	Avg (%)	No.	range (%)	Avg (%)
Deery 101SD	7	4-33	19	7	4-33	19	2	1-10	5	0	-	-
Deery 101ELT	8	5-38	21	2	1-10	5	6	4-29	16	2	1-10	5
Roadsaver 231SD	7	4-33	19	3	2-14	8	18	11-86	48	5	3-24	13
Roadsaver 522	2	1-10	5	6	4-29	16	6	4-29	16	7	4-33	19
Mod 4 3405	2	1-10	5	13	8-62	35	10	6-48	27	4	2-19	11
3405 M	3	2-14	8	4	2-19	11	10	6-48	27	12	7-57	32
Elastoflex 72	6	4-29	16	8	5-38	21	10	6-48	27	4	2-19	11
MacSeal 6690	10	6-48	27	6	4-29	16	10	6-48	27	5	3-24	13



(a) Highmore test site (b) Yankton test site

Figure 31 No distress (ND) percentage and average secondary cracking (SC) and adhesion/cohesion failure (A/CF) for first winter inspection

At the Highmore test site, the estimated percentage (Figure 31) suggest the Roadsaver 522 (Crafco) and Mod 4 3405 (Right Pointe) were performing better as observed during the 1st winter inspection. They have the largest number of 48 in. crack segments with no distress and the smallest number of secondary cracking failures. At the Yankton test site, the Deery 101 and Roadsaver 231SD sealants (Crafco) were performing better also because of the large percentages of no distress and small percentages of secondary cracking and adhesion/cohesion failures.

9.4.2 Second winter inspection (after chip seal)

The total counted photographs with the no distress condition over the full photographed 48 in. crack length and this percentage of total 84 ft length for both the Highmore and Yankton sites is shown in Table 20 for the second winter inspection. The counted photos for the secondary cracking and adhesion/cohesion failure conditions, the percentage ranges, and estimated average percentages are shown in Table 21. Chip sealing was not performed near the intersection of Hwy 50 and Hwy 210 at the Yankton test site because of a future right-turn lane construction project. The crack sealants in this turn-lane area (Roadsaver 231 SD, MacSeal 6690, Elastoflex 72, and) and two 12 ft crack lengths of Deery 101 SD) were therefore not chip sealed. These sealants are separated in Table 21 using the secondary cracking (SC) and adhesion/cohesion failure conditions used to assess crack sealants before the chip seal (Table 16). A bar graph showing the crack sealant conditions for the evaluations before and after chip sealing are shown in Figure 32.

Table 20 Number of photographs with no distress and crack length percentage

	No distress (ND)			
Product	Highmore	%	Yankton	%
Deery 101SD (a)	5	24	4	19
Deery 101ELT	2	10	0	0
Roadsaver 231SD (b)	1	5	3	14
Roadsaver 522	14	67	7	33
Mod 4 3405	3	14	8	38
3405 M	3	14	17	81
Elastoflex 72 (b)	0	0	8	38
MacSeal 6690 (b)	3	14	9	43

(a) Includes 15 photos with chip seal, 6 photos without chip seal
(b) Cracks not chip sealed

Table 21 Approximate percentages of sealants with observed conditions

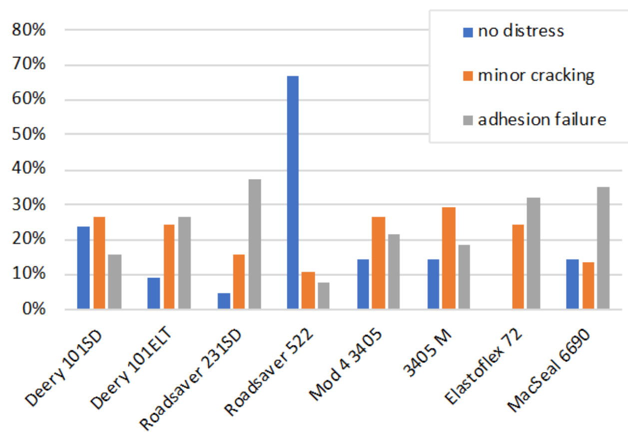
	Minor Cracking (MC)						Adhesion (AF)					
	Highmore			Yankton			Highmore			Yankton		
Product	No.	range (%)	Avg (%)	No.	range (%)	Avg (%)	No.	range (%)	Avg (%)	No.	range (%)	Avg (%)
Deery 101SD (a)	10	6-48	27	11	9-73	41	6	4-29	16	3	3-20	11
Deery 101ELT	9	5-43	24	17	10-81	46	10	6-48	27	4	2-19	11
Roadsaver 231SD	6	4-29	16				14	8-67	38			
Roadsaver 522	4	2-19	11	10	6-48	71	3	2-14	8	4	2-19	11
Mod 4 3405	10	6-48	27	8	5-38	21	8	5-38	21	5	3-24	13
3405 M	11	7-52	30	4	2-19	11	7	4-33	19	0	-	0
Elastoflex 72	9	5-43	24				12	7-57	32			
MacSeal 6690	5	3-24	13				13	8-62	35			
	Secondary Cracking (SC)						Adhesion/Cohesion Failure (A/CF)					
without chip seal				Yankton						Yankton		
Deery 101SD (b)				1	2-17	9.4				0	-	0
Roadsaver 231SD (c)				0	-	0				15	9-71	40
Elastoflex 72 (c)				9	5-43	24				4	2-19	11
MacSeal 6690 (c)				3	2-14	8				6	4-29	16

(a) Includes 15 photos with chip seal
(b) Includes 6 photos without chip seal
(c) cracks not chip sealed

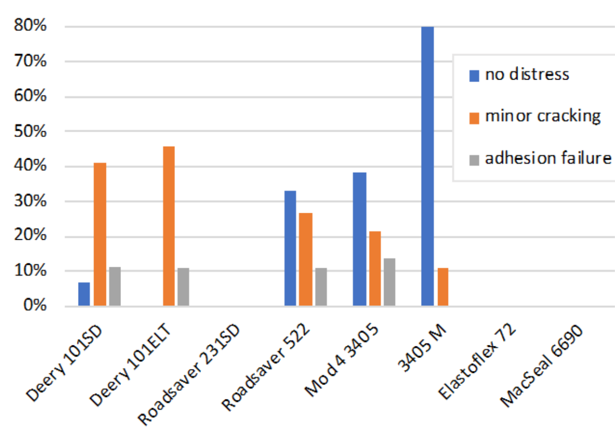
At the Highmore test site, the estimated percentages shown in Figure 32a) suggest Roadsaver 522 (Crafco), was performing better than the other sealants as observed during the 2nd winter inspection. This sealant had the largest number of 48 in. crack segments with no distress and the smallest numbers of minor cracking and adhesion failures. At the Yankton test site (Figure 32b), the 3405M (W.R. Meadows) had the highest percentage of no distress (ND) conditions when observed after the chip seal. Without the chip seal, as shown in (Figure 32c), Deery 101SD (Crafco) was performing better than Elastoflex 72 (Maxwell Products) and MacSeal 6690 (McAsphalt).

9.4.3 Adjacent shoulders without chip seal (Yankton site only)

Chip sealing maintenance by the Yankton area covers only the 12ft lane widths and not the shoulder. This provides an opportunity to investigate the crack seal performance with and without a chip seal.

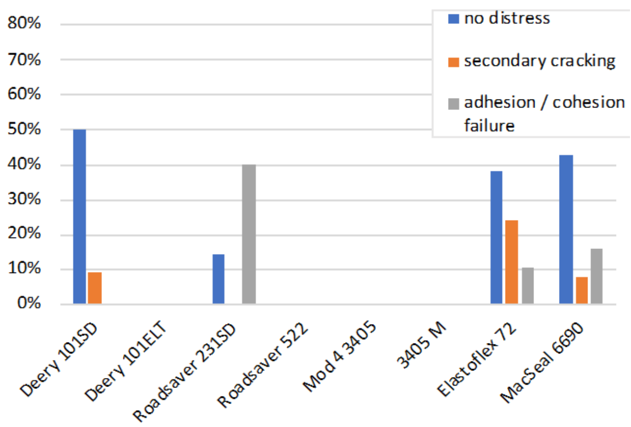


(a) Highmore test site



(b) Yankton test site after chip seal

The Evaluation of Past Field Performance (Section 7.2) documented fair to poor crack sealant performance after chip sealing maintenance was performed in 2014. A potential reason may be the chip seal maintenance that is commonly performed the following year after crack sealants are installed. The relatively stiff chip seal material compared with the crack sealant creates a mechanical challenge for the crack sealant material to extend over the routed reservoir width. A schematic of the crack sealant mechanics before and after the chip sealant is shown Figure 33. As illustrated in the Figure, the benefit of the ¾ in. routed reservoir width is lost after the chip seal is placed on top of the crack sealant.



(c) Yankton test site without chip seal

Figure 32 Estimated average percentage of observed crack conditions

Sealant must extend full contraction width over a crack in sealant

Sealant extension: 21% @ Yankton x ¾ in. = 0.16 in.
47% @ Highmore x ¾ in. = 0.35 in.

Rigid chip seal material

¾ in. routed reservoir

crack sealant

Observed adhesion failure

crack width: 0.02 - 0.1 in.

crack width: 0.02 - 0.1 in.

Figure 33 Joint sealant mechanics before and after chip seal

To assess a potential crack sealant performance barrier due to a chip seal, shoulder photos taken at the Yankton site were compared with the adjacent chip sealed portion of the roadway. An example of these comparison photos is shown in Figure 34. Additional photos are included in Appendix H.

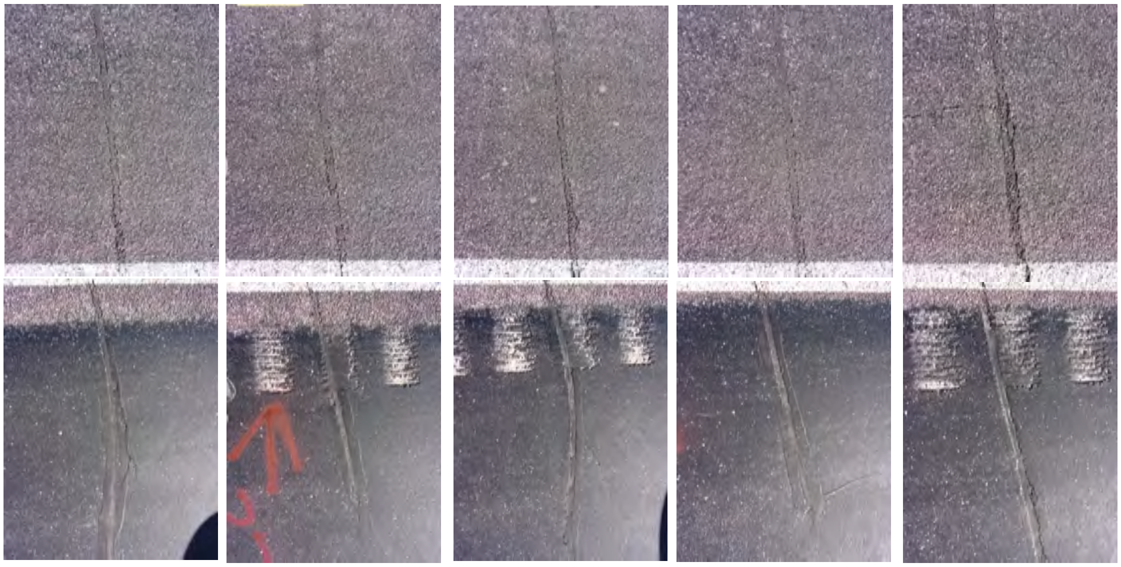


Figure 34 Shoulder crack sealant comparison photos

From Appendix H, the three most significant adhesion failure/minor cracking sealant distresses were selected and are shown in Figure 35. The examples shown are not the most severe levels of adhesion failures or cracking observed at either test site. Without confidently knowing the penetration of the observed chip sealant distress, it is difficult to assess the sealants performance with and without the chip seal from the shoulder observations. The comparison photos in Figure 35, do however suggest the sealant extension is distributed over the routed reservoir dimension and are not concentrated at the edges of the reservoir and shown schematically in Figure 33.

(a) Deery 101 ELT (Crafco)

(b) Deery 101 ELT (Crafco)

(c) Mod 4 3405 (Right Pointe)

Figure 35 Shoulder performance compared with adjacent chip sealed lane

9.5 Sealant Performance Index

The three metrics used to assess the performance of eight different crack sealants at two test sites include approximate percentages of 84 ft of observed crack length with; 1) no distress, 2) minor cracking/secondary cracking, and 3) adhesion/cohesion failures. To quantify the overall performance of the crack sealants after the second winter inspection, an index was developed that subtracts a weighted, less desirable crack sealant characteristic (pavement cracking and sealant failure) from the desirable no distress condition.

The estimated percentages of the sealant conditions shown in Table 21 were used to calculate the index. The percentages of no distress, minor cracking/secondary cracking, and adhesion/cohesion failures observed at each test section do not add up to 100%. This uncounted percentage of the 84 ft. length was assumed to be in satisfactory condition, and was denoted as 'OK'. This performance condition was added to the other conditions to obtain a crack sealant index (CSI) using the following equation.

$$\boldsymbol{S_{OK} + aS_{ND} - b(S_{SC} \text{ or } S_{MC}) - c(S_{A/CF} \text{ or } S_{AF})} \qquad \textbf{\textit{Equation} 3}$$

where:

- S_{OK} = remaining crack sealant percentage not counted by the ND, MC, SC, AF, or A/CF conditions
- S_{ND} = percent of sealant with no distress
- S_{SC} = percent of sealant with secondary cracking not covered by a chip seal
- S_{MC} = percent of sealant with minor cracking covered by a chip seal
- $S_{A/CF}$ = percent of sealant with adhesive/cohesive
- S_{AF} = percent of sealant with adhesion failure covered by a chip seal

The coefficients a, b, and c are used to increase the weight of the overall index for desirable performance conditions (ND) and least desirable characteristics. Values of a = 2, b = 1, and c =

1.5 were selected for this study. The condition percentages used in Equation 3 to calculate the crack sealant indices (CSI) are shown in Table 22 for the second winter inspection.

Table 22 Crack sealant index with condition percentage inputs

	Second Winter Inspection (after chip seal)									
	Highmore					Yankton				
Product	S_{OK}	S_{ND}	S_{MC}	S_{AF}	CSI	S_{OK}	S_{ND}	S_{MC}	S_{AF}	CSI
Deery 101SD	33.3	23.8	26.8	16.1	0.3	40.8	19.0	32.1	8.0	0.4
Deery 101ELT	39.6	9.5	24.1	26.8	-0.1	43.8	0	45.5	10.7	-0.2
Roadsaver 231SD	41.7	4.8	16.1	37.5	-0.2	45.5	14.3	0	40.2	0.1
Roadsaver 522	14.6	66.7	10.7	8.0	1.3	29.2	33.3	26.8	10.7	0.5
Mod 4 3405	37.5	14.3	26.8	21.4	0.1	27.1	38.1	21.4	13.4	0.6
3405 M	37.5	14.3	29.5	18.8	0.1	8.3	81.0	10.7	0	1.6
Elastoflex 72	43.8	0	24.1	32.1	-0.3	27.1	38.1	24.1	10.7	0.6
MacSeal 6690	37.5	14.3	13.4	34.8	0.0	33.0	42.9	8.0	16.1	0.9

The better and poorer performing crack sealants identified from the average sealant condition percentages shown in Figure 32 are also reflected in the CSI ratings shown in Table 23. The shaded sealants for the Yankton site shown in Table 23 test site did not have a chip seal installed because of the turn lane construction at the Yankton site (Section 9.4.2). The conditions used to assess these sealants without a chip seal included secondary cracking and cohesion distress, compared with minor cracking and adhesion failure used for the chip sealed sealants. This aspect of the evaluation should be noted when comparing the shaded sealants with the others shown in Table 22.

9.5.1 Laboratory test results as an indicator of sealant performance

Standard material tests according to ASTM D6690 were performed by the SDDOT materials lab. Results of the tests and the acceptance criteria are shown in Table 24. Also shown is the unit weight and pouring temperatures measured during installation. SDDOT's Standard Specification 871 requires a maximum unit weight of 9.35 lb/ft^3. Values shown in red for all test results are outside of the ASTM or SDDOT specification or the recommended pouring temperatures from the sealant manufacturer.

Table 23 Overall sealant performance index

Highmore	CSI	Yankton	CSI
Roadsaver 522	1.3	3405M	1.6
Deery 101SD	0.3	MacSeal 6690	0.9
Mod 4 3405	0.1	Mod 4 3405	0.6
3405 M	0.1	Elastoflex 72	0.6
MacSeal 6690	0	Roadsaver 522	0.5
Deery 101ELT	-0.1	Deery 101SD	0.4
Roadsaver 231SD	-0.2	Roadsaver 231SD	0.1
Elastoflex 72	-0.3	Deery 101ELT	-0.2

Table 24: Specifications for Type IV Crack Sealant (from ASTM D6690)

ASTM Test	Spec	Deery 101SD	Deery 101ELT	Roadsaver 231SD	Roadsaver 522	Mod 4 3405	3405M	Elastoflex 72	MacSeal 6690

Cone Penetration at 25°C	90-150	123	105	127	90	91	124	105	118
Softening Point (°C)	> 80	p	p	p	p	p	p	p	p
Bond (non-immersed)	(1)	y	y	y	y	y	y	y	y
Resilience (%)	> 60	60	50	64	56	75	64	50	79
Asphalt Compatibility	(2)	y	y	y	y	y	y	y	y
Other Data									
Pouring temp									
Highmore		370(5)	370(5)	380	390	380	385	350(3)	365
Yankton		400	385	380	365(3)	350(4)	370	380	380
Unite weight (lb/ft^3)	< 9.35	9.35	9.37	9.33	8.72	9.29	9.28	9.96	9.34

(1) Three 12.5 ± 0.2 mm specimens, pass 3 cycles at 200% extension at -29°C

(2) No failure in adhesion, formation of any oily exudate at the interface between the sealant and asphaltic concrete or other deleterious effects on the asphaltic concrete or sealant when tested at 60°C

(3) Recommended pouring temp = 380°F

(4) Recommended pouring temp = 370-390°F

(5) Recommended pouring temp = 380-400°F

The sealant temperatures measured during installation for Elastoflex 72 and Deery 101ELT at the Highmore site were 30°F and 10°F, respectively cooler than manufacturer recommendations. These placement temperatures may have contributed to the poorer performance relative to the other materials. Low placement temperatures for Roadsaver 522 and Mod 4 3405 (15°F and 20°F cooler respectively) at the Yankton site and Deery 101SD at the Highmore site (10°F cooler), however, did not have relatively poorer performance relative to the other materials.

Low resilience measurements reported by the SDDOT materials lab did not seem to affect the good performance of Roadsaver 522 at the Highmore site, however low resilience measurements for Elastoflex 72 and Deery 101ELT may have contributed to the poor performance at the Highmore and Yankton sites, respectively. Because of the inconsistence performance of the materials at the two test sites, confident conclusions relating low resilience measurements are not drawn. A trend, however, is observed that lower resilience measurements (50 compared with 60) may have contributed to the performance of two sealants, compared with better performance for materials with a resilience measurement of 56 compared with 60.

10.0 SDDOT STANDARD SPECIFICATIONS FOR ASPHALT CRACK SEALANTS

Standard specifications for State departments of transportation bordering South Dakota were reviewed to identify the current state of practice for asphalt crack sealing operations. Iowa, Nebraska, Minnesota, North Dakota, Wyoming, and Montana, were selected because of their proximity to South Dakota and overlapping climate conditions.

South Dakota's current crack-sealing specifications and construction practices are found in Sections 350 and 871 of the SDDOT Standard Specifications for Roads and Bridges (2015). A summary of the relevant specifications for these Standards is included below, followed by a comparison to other State Specifications.

10.1 SDDOT Standard Specification 350; Asphalt Concrete Crack Sealing

Routing:

Routing equipment shall be mechanical, power driven, and capable of cutting a reservoir to the required dimensions. Equipment designed to plow the cracks to dimension will not be permitted. Cracks which are less than ¾ in width or depth require routing to a width and depth of 3/4 to 7/8 in. Cracks which are 3/4 in. or greater in width or depth do not require routing, but shall be thoroughly cleaned of foreign material to a depth equal to the width of the crack. Walls of the finished reservoir shall be vertical and the reservoir bottom shall be flat. Routing will not be allowed when the roadway is wet.

Cleaning:

Cleaning shall be accomplished with an air compressor with a minimum of 125 cubic feet per minute output with a maximum ¾ in nozzle. The compressor shall be equipped with traps capable of removing all free water and oil from compressed air. Reservoirs and cracks shall be thoroughly cleaned of dust, dirt, and loose materials so the reservoir is clean and dry at the time the blocking medium or sealant is applied. If left overnight, reservoir must be recleaned. All routed asphalt and material resulting from reservoir preparation shall be removed from the surface before area is opened to traffic.

Sealing:

Cracks 3/8 in or greater in width shall be filled with a blocking medium to ensure a nominal sealant depth equal to the width of the reservoir. Sealant materials must be placed within 72 hours of routing with no visible signs of moisture on the roadway or reservoir during application. Sealant handling, mixing, and application temperature restrictions shall conform to the manufacturer's recommendations and shall be applied with a pressure type applicator. When applying on transverse and longitudinal cracks that are more than 12 inches from a lane line, the reservoir shall be overfilled and squeegeed to provide a film of sealant on the surface 1 to 2 in. on both sides of reservoir. For cracks within 12 in. of a lane line, the reservoir shall be overfilled and squeegeed to provide a film of sealant up to 1 in on both sides of the reservoir. Squeegee shall be a "U" shaped device which produces a full, uniform, and neat appearing reservoir. Other devices require approval by the Engineer. A blotting material (toilet tissue or an approved de-tacking agent) shall be placed over the sealant immediately after placement at intersections, super elevated curves, urban areas, grades steeper than 4%, and other locations specified on plans. Blotting material was required when traffic is allowed to cross a sealed area before track free status has been achieved. At the Contractor's expense, any part of a sealed reservoir damaged by traffic will be repaired.

Seasonal and Temperature Limitations

Routing and sealing of asphalt will be permitted only during daylight hours between April 1 and June 30 and between August 15 and November 30. Application of the sealant will only be allowed when the pavement surface temperature is at least 35°F and rising, and when the temperature is between 40°F and 85°F. Humidity must be less than 75%.

10.1.1 Comparison with other State Specifications

Differences from South Dakota's construction specifications for the six selected comparison states are shown in Table 25.

Notable difference between specifications for South Dakota and specifications for Iowa, Nebraska, Wyoming, and Montana is the routed reservoir dimensions. Reservoir widths are ½ in. for Wyoming and Nebraska, 3/8 in. wide for Iowa, and 1-½ in. wide for Montana. Narrower reservoir widths are more demanding on sealant extension requirements and may be appropriate for states with warmer winter conditions that produce smaller pavement contractions. The wider reservoir used by Montana was based on advantages reported by Ponniah and Kennepohi (1996). This research concluded that a 4:1 routed reservoir dimension promotes good bonding and improves the sealant material's capability of extending at low temperatures without rupturing. This research also noted the reservoir dimension increases the productivity of the routing machine.

10.1.2 Applicable practices from other states:

One crack sealing practice from other states that SDDOT could consider adopting is the use of a wider routed joint width than ¾ in. As documented in the literature review (Section 5.1.1), wider routing configurations have been shown to improve sealant extendibility for low temperature applications. A more recent study by Gnatenko et al. (2016) recommends a maximum width of 1.2 in. to minimize the area of sealant in contact with vehicle tires to avoid its pressing out of the reservoir. The only state in Table 25 using a router width greater than ¾ in. is Montana, where a 3:1 ratio (1.5 in. wide x ½ in. deep) is specified. The benefits of increasing the reservoir width in South Dakota, however, might be limited, however because of chip sealing activities that are performed the following summer, as described in 9.4.3.

Table 25 Notable differences of crack sealing specifications in neighboring states.

	Iowa (Standard Specifications for Highway and Bridge Construction)	**Nebraska** (Standard Specifications for Highway Construction)	**Minnesota** (MnDOT Special Provision 2331)
Routing	Cracks < 3/8 in., 3/8 in. wide x 1/2 in. deep reservoir	Cracks < 3/8 in., ½ in. wide x ¾ in. to 1 in. deep reservoir	Typically ¾ in. x ¾ in. reservoir, different sizes may be specified.
Cleaning	-	Cracks > 3/8 in., cleaned by sandblasting or brushing and air blowing techniques	-
Sealing	Use V-shaped squeegee. Excess sealant shall not exceed 1/2 in. on either side of crack edge.	A hot air heat lance shall be used to warm the sidewalls of the crack immediately prior to placing the sealant. The crack shall be slightly overfilled with sealant and squeegeed to surface level leaving a 2 to 4 in. width of sealant over the crack	Wand followed by a "V" shaped squeegee or by a round application head having a concave underside. The maximum width of the application head shall be 2 inches for standard coverage. The maximum width of the application head shall be 4 inches for multi-crack locations. The maximum film thickness of the overband is limited to 0.125 inches deep.
Limitations	No crack sealing after September 30, or if ambient air temperature is above 40°F.	No temperature or seasonal limitations specified.	Dry and rising temperatures > 50°F. Work completed before September 16 in Northern spring load restriction zone, before October 16 for other zones.
	North Dakota (Standard Specifications for Road and Bridge Construction)	**Wyoming** (Standard Specifications for Road and Bridge Construction)	**Montana** (Standard Specifications for Road and Bridge Construction)
Routing	-	Cracks < 1/2 in., ½ in. wide x ¾ in. deep reservoir	Cracks < 1 in., 1-½ in. wide by ½ in. deep reservoir.
Cleaning	-	Use compressed air heat lances to prepare cracks.	-
Sealing	-	Provide a U-shaped squeegee for smoothing the sealant. Seal cracks to the specified flush or recessed configuration	Do not exceed 2 inches of spread sealant on the roadway.
Limitations	-	Pavement inside crack must be at least 40°F and dry weather.	Ambient temperature is 50°F or higher or when surface temperature is between 35°F and 120°F

Future research of interest would include test sections where chip sealing maintenance is delayed, to investigate the length of time a crack sealant is effective as a stand-alone treatment. In this research routed reservoir widths of 1 in. and 1.25 in. (ratios 1.33:1, 1.67:1) could also be included to confirm that potential improved sealant performance applies to South Dakota's crack sealant operations. The high percentage of crack sealants with no distress at the Yankton test site (Figure 32c) that were not chip sealed due to the turn lane construction suggest that a delayed chip seal could be implemented without reducing the pavement service life. Future research should also determine the best performing crack sealant for a delayed chip seal, as only three of the eight sealants in this investigation were assessed for the entire 84ft length.

10.2 SDDOT Standard Specification 871; Asphalt Concrete Crack Sealant

Crack sealant materials shall conform to ASTM D6690 Type IV, shall not weigh more than 9.35 lb/ft^3 and have performed satisfactorily based on Department analysis may be used. A listing of acceptable products meeting ASTM D6690 Type IV requirements may be obtained from the Department's Approved Products List. Products on the Department’s Approved Products List for joint sealant for asphalt over long jointed concrete pavement may also be used. The blocking medium shall be an inert, compressible material which is compatible with the sealant.

10.2.1 Approved Products List for South Dakota and Comparison States

A list of crack sealant materials that are included in the approved product list for South Dakota and the selected comparison states are shown in Table 26. The first eight materials (shaded) are the products evaluated for the current research project. All materials listed meet ASTM D6690 Type IV specifications. Most of the materials on the Nebraska Department of Transportation Approved Product list meet ASTM D6690 Type II materials specifications, which requires a 50% extension requirement at -29°C. Because South Dakota specifications require ASTM D6690 Type IV classification (200% extension at 29°C) only the most recent Type IV approvals are included for Nebraska. Hot-poured elastic sealants are not included on Wyoming’s Qualified Products List, however WYDOT’s Standard Specifications for Road and Bridge Construction requires crack sealant products meet ASTM D6690 with modifications. Minnesota also requires modifications to ASTM D6690, which are shown in Table 27 with Wyoming requirements. The North Dakota Department of Transportation does not maintain an Approved Products List for construction related materials.

Table 26 Approved Product Materials for South Dakota and Comparison States meeting ASTM Specification D6690, Type IV with exceptions noted.

Product	Manufacturer	SD	IA	NE	MN	WY[(a)]	MT
Included in Research							
Macseal 6690-4	McAsphalt	X	X		X[(b)]		X
101 ELT	Crafco	X			X[(b)]		X
Road Saver 231SD	Crafco	X	X				
101SD	Crafco	X	X				
3405 M	WR Meadows	X	X				
Mod 4 3405	Right Pointe						
Elastoflex 72	Maxwell				X[(b)]		X
Road Saver 522	Crafco	X[(c)]			X[(b)]		X
Other Materials							
Durafill 3725	P&T Products				X[(b)]		
Sealtight 3405 MLR	WR Meadows				X[(b)]		
RP Type 3725	Right Pointe				X[(b)]		
Elastoflex 71	Maxwell		X				
Product #9030	SemMaterials		X				
RP Type 4 ELT	Right Pointe		X				X[(d)]
W22787	Crafco (2018)			X			
72396F	Right Pointe (2019)			X			

(a) Must meet ASTM D 6690 Type IV with modifications from WY Specification 807.2

(b) Must meets ASTM D 6690 Type IV with modifications from MN Specification 3725

(c) SD Sealant Approved for *Asphalt Concrete over Long Jointed Concrete Pvmt*. Other SD materials are approved under *Hot poured Elastic Joint Matl & Backer Rods*

(d) 3405 Modified MT

Table 27 ASTM D6690 Type IV specification limits with MnDOT and WYDOT modifications

Test	ASTM D6690 Type IV	MN Specification 3725	Wyoming Subsection 807.2
Cone Penetration @25° C	90 - 150 mm	100-150 mm	83 - 162 mm
Softening Point °C	80 minimum	-	74 minimum
Bond, non-immersed	Three 12.5 ± 0.2 mm Specimens pass [(a)] 3 cycles at 200 % ext. at -29°C	-	-
Resilience	> 60%	30%-60%	
Asphalt Compatibility	Pass [(b)]	-	

(a) The development at any time during the test procedure of a crack, separation, or other opening that at any point is over 6 mm deep, in the sealant or between the sealant and concrete block shall constitute failure of the test specimen. The depth of the crack, separation or other opening shall be measured perpendicular to the side of the sealant showing the defect.

(b) There shall be no failure in adhesion, formation of an oily exudate at the interface between the sealant and asphaltic concrete or other deleterious effects on the asphaltic concrete or sealant when tested at 60°C.

11.0 SDDOT APPROVED PRODUCT LIST

The product evaluation procedure for adding materials to SDDOT's Approved Products List is described below and compared with processes from the comparison states. Differences between other states and opportunities for revisions are included.

11.1 Product evaluation Procedures.

South Dakota

The South Dakota Department of Transportation's Product Evaluation Procedure includes several steps which are summarized below and represented in a flowchart in Figure 36.

1. Receipt of the product evaluation form by the Certification Engineer.
2. Upon receipt of sufficient information, the Certification Engineer will review the submitted information, conduct an initial screening of the product, and determine if it should be sent to committee.
3. The Committee will review the submitted information and conduct the evaluation. If the committee decides to initiate a formal evaluation, a literature review, lab testing, and/or field testing will be performed. Based on the results of the evaluation, the committee will either reject, continue with additional analyses, or approve and add the product to the Approved Product List.

Relative to approving asphalt crack sealants, the flowchart shown in Figure 36 potentially simplifies to the process shown below, creating an efficient path toward adding a new sealant material to the APL.

Initial screening	→	Does the material meet ASTM D6690 Type IV?
Committee Review	→	Do other DOT's use it?
Evaluation	→	Request lab sample and perform tests to confirm ASTM D6690 requirements are satisfied. Compare with other material results
	→	Review performance from recent installations
Approval	→	Add to Approved Products list.

Conversely, if a material does not have a sufficient history of successful performance, or is lacking other data, the certification engineer or the review committee can pause the approval process and request additional information.

North Dakota

NDDOT does not maintain an Approved Products List for construction related materials. The process for approving a material for a given project is contractually based. The contract may require either or both of the following as the basis for approval and acceptance of material:

1. Sampling, testing, and inspection; and
2. A Certificate of Compliance.

If a new product appears to have a benefit beyond the current specifications, or if a specification does not exist, the department will review the information provided by the vendors who submit a 'New Products Submittal'.

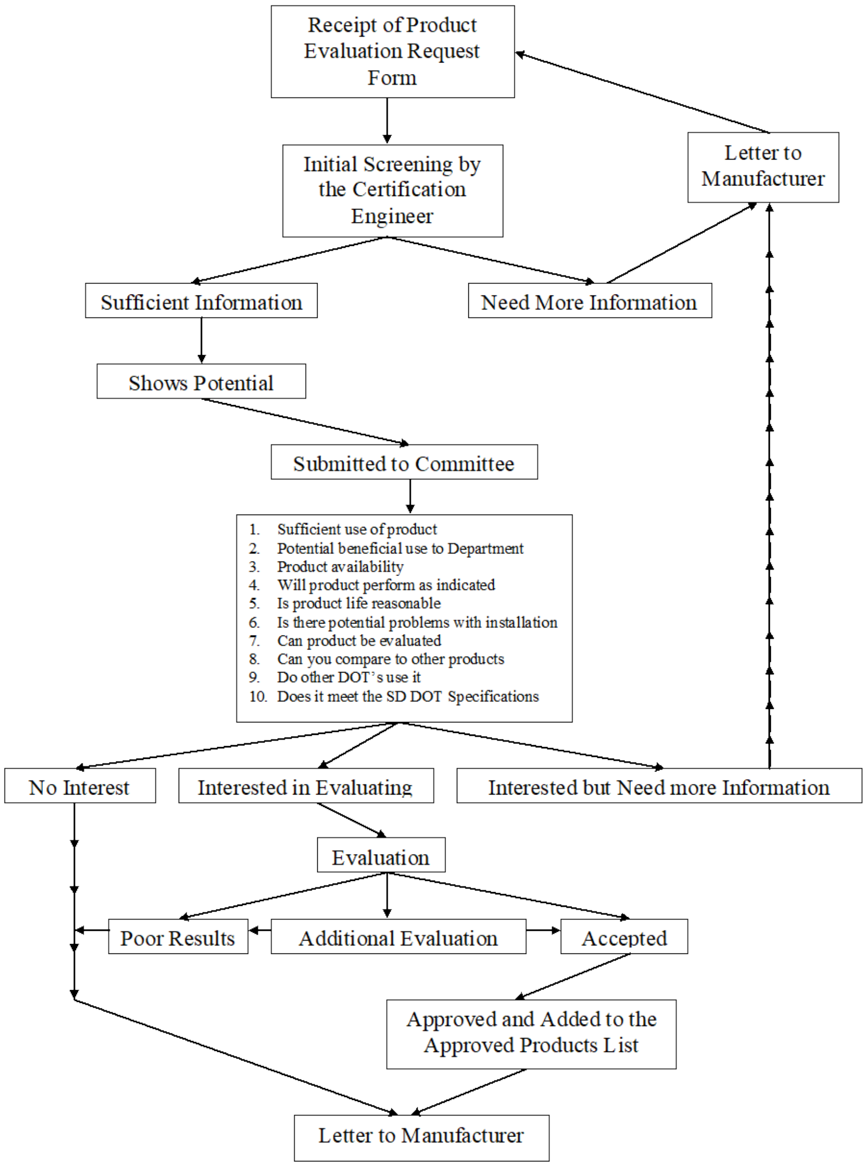


Figure 36 SDDOT product evaluation procedure

Iowa

To obtain approval, the manufacturer shall submit the following to the Iowa Department of Transportation, Construction and Materials Bureau.

1. Product identification including brand name and product number
2. Technical literature and MSDS for the product
3. AASHTO National Transportation Product Evaluation Program (NTPEP) evaluation report for the product.

Montana

Prospective producers interested in submitting their product for QPL qualification or revision should send an e-mail to the MDT QPL List or a written request to: Montana Department of Transportation, Materials Bureau. After receiving the proper documentation, MDT will contact the producer. Samples may be requested for analysis.

To be considered for qualification, the product must have been in production for at least 6 months. The producer must provide a copy of the producer's quality control plan for this product to MDT. This plan must show that their quality control (QC) facilities actively participate in the QC of the product. MDT will place the acceptable material on the QPL after confirming the material meets specifications; there is an adequate QC plan in place for product productions; and no other Department concerns exist.

Once a product is listed in the QPL, any change in formulation, manufacturing process, or manufacturing location must be reported to MDT on the appropriate forms. Any changes in the material require resubmission for requalification.

Wyoming:

Form T-131, Manufactured Products Received, lists the documentation requirements (Acceptance Criteria) for manufactured goods and products where documentation provided by the manufacturer or supplier is required to verify compliance to the applicable specification. Included in Form T-131 are fields containing the material / product name, acceptance criteria, bid item number(s), and, if available, the plan quantity. Final manufactured products added to the project are sent to the Resident Engineer and Prime Contractor for each project.

Minnesota

Applicants send a personalized submittal package to the Chemical Lab Director at the MnDOT Office of Materials and Road Research. Submittal package should include:

1. Completed New Products Application Form
2. Manufacturer contact name, address, phone number and email address
3. Product Data Sheets on all components including application directions
4. Material Safety Data Sheets on all components
5. Performance History References in a cold climate
6. Certification that products meet Minnesota Statute 115A.9651 requirements for heavy metals
7. List of location for any field trials where your product is being evaluated
8. List of state DOT Qualified Products Lists that lists your product
9. One (1) manufactured lot sample. Sample shall be taken from production lot. Include the name and address of the manufacturing facility, date of manufacturer and lot number.
10. Complete MnDOT Office of Environmental Services Hazardous Evaluation Process

If the manufacturer has participated in a cold climate NTPEP Crack Sealer Evaluation, they submit the NTPEP data with the submittal package. If no cold climate NTPEP crack sealant evaluation is available, a provisional approval will be granted pending a three-year field evaluation on a Minnesota project. The manufacturer is limited to installing the product on only one project during the field evaluation period. The product will be given full approval after a successful three-year field evaluation. The product will continue to remain on the (APL) in successive years provided it continues to perform satisfactorily for the expected life of that product. Any change in product formulation without MnDOT approval shall result in a product being removed from the (APL). MnDOT reserves the right to add additional tests at any time. In addition, MnDOT reserves the right to remove any manufacturer from the (APL) based on field performance as observed by MnDOT or by another agency.

Nebraska

Similar to South Dakota, the Nebraska Department of Roads provides a flowchart summarizing the approval process shown in Figure 37. One notable difference in Nebraska's flowchart from South Dakota's process is a missing formal path to request additional information. In Nebraska's case, the product is either approved or rejected after review by the product team.

11.1.1 Applicable processes from other states

South Dakota's evaluation process to include new materials to the Approved Products List is similar to other states. One item from Minnesota's submittal package that could be more specifically included on South Dakota's evaluation request form would be a list of other State DOT's that list the product on their Qualified Products List. While this information would likely be included in the existing question shown in Figure 38 from SDDOT's evaluation form, specifically asking for this information would clarify if a product is approved or only tested.

A second opportunity to strengthen SDDOT's approved product list would be to include language similar to Minnesota and Montana related to a change in product formulation. Montana requires that manufacturers report any changes in formulation, manufacturing process, or manufacturing location and these changes require resubmission for requalification. Similarly, Minnesota informs manufacturers that any change in formulation without MnDOT approval will automatically remove a product from their APL and that MnDOT reserves the right to add additional tests at any time. In South Dakota, this addition could clarify the differences between the sealant Deery 101 and Roadsaver 231 which are currently on SDDOT's APL with the products Deery 101ELT, Deery 101SD, and Roadsaver 231SD which were evaluated as part of this investigation.

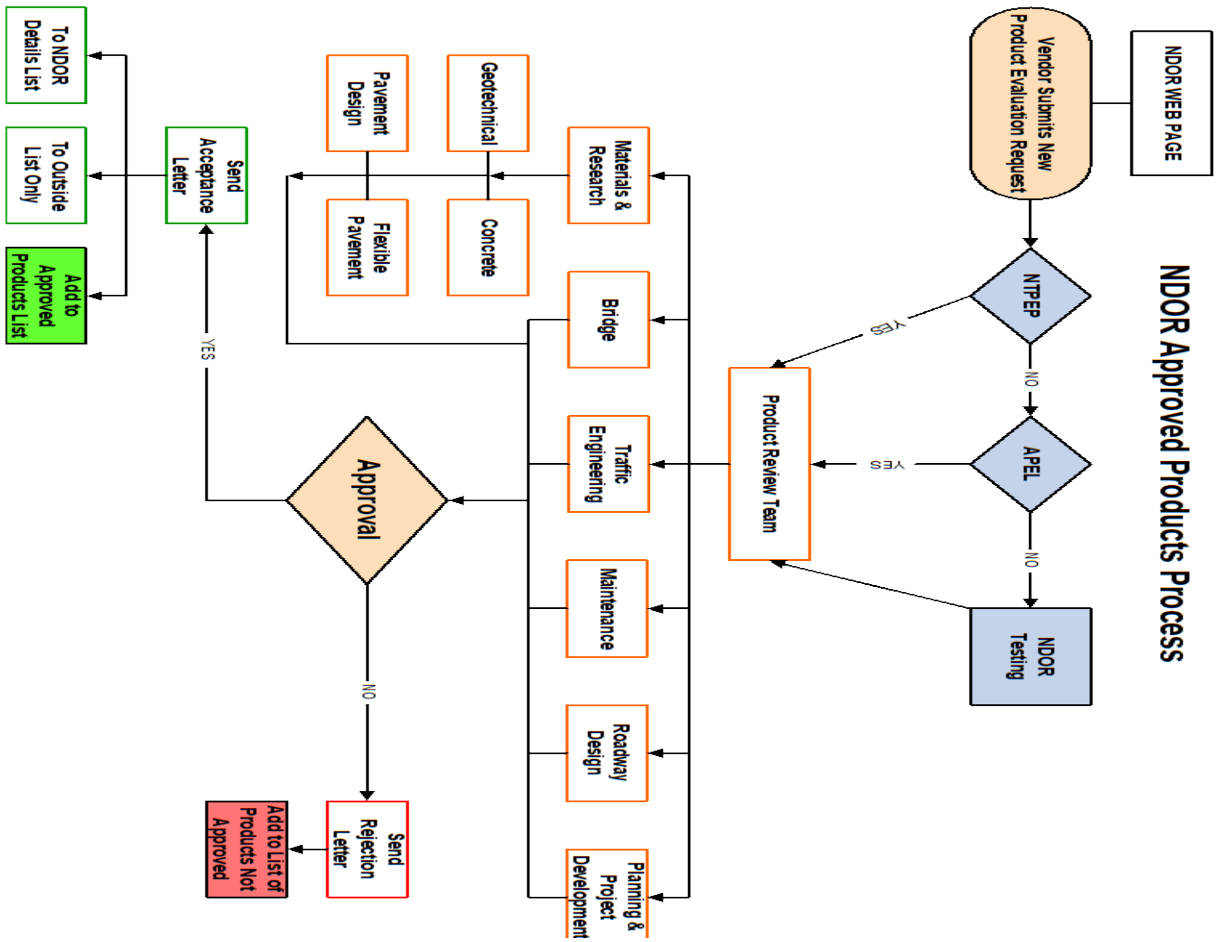


Figure 37 Nebraska Department of Roads product evaluation procedure

Other States in Use or Testing	State:	Contact:	Phone:
	State:	Contact:	Phone:
	State:	Contact:	Phone:

Figure 38 Portion of South Dakota's product evaluation

12.0 FINDINGS AND CONCLUSIONS

The objectives of this research were to; 1) Evaluate ASTM D6690 Type IV crack sealants on the SDDOT Approved Products List and promising new crack sealants for their suitability for use in South Dakota, 2) Review the South Dakota Standard Specifications for Roads and Bridges for adequacy in regard to selecting suitable asphalt crack sealants, and 3) Review and recommend changes to SDDOT's Approved Product List procedures regarding crack sealants. The findings and conclusions for each objective are included below.

12.1 ASTM D6690 Type IV crack sealant evaluation

Eight different crack sealants were observed at test sites located near Highmore, SD and Yankton, SD. The performance of these sealants was evaluated during two winter inspections, where pavement contractions were highest and sealant distress was most visible. Eighty-four feet of crack length was observed and documented for each sealant where approximate percentages of no distress, cracking, and adhesion failures were documented.

12.1.1 First Winter inspection, 5 months after sealant installation, before chip seal.

- Crack sealant performance was generally better at the Yankton test site. At this site, Deery 101SD, Deery 101ELT, and Roadsaver 231SD had the highest percentages of crack length with no distress. In contrast, Roadsaver 231 SD had the highest percentage of adhesion / cohesion failures at the Highmore site. Installation data and subsequent lab tests did not reveal a possible explanation to the different sealant performance at the two sites.

- The highest performing sealant at the Highmore site was Mod 4 3405. This sealant, however had the largest percentage of secondary cracking at the Yankton site. The contrasting and relatively poorer performance of Mod 4 3405 at the Yankton site could be related to the 20-degree cooler pouring temperature than recommended by the manufacturer.

- At the Highmore site, Roadsaver 231SD had the highest percentage of observed adhesion / cohesion failures, which conflicts to the high percentage of no distress observed for this sealant at the Yankton site. The performance of Mod 4 3405 was also poorer at the Highmore site, where the hi

- Results of this research found that sealants generally performed better at the Yankton site (200 miles SE of Highmore) and is likely due to the smaller measured pavement contraction of 21% measured at the Yankton site and 47% measured at the Highmore site. Other explanations for the inconsistent sealant performance could be the bituminous overlay on a concrete pavement at the Yankton site or the different traffic characteristics and/or volumes between the two sites.

12.1.2 Second winter inspection, 1.5 years after sealant installation, after chip seal

- The performance of eight crack sealants were ranked using a calculated crack sealant index (CSI) that subtracted a weighted percentage of crack sealant length with observed cracking or adhesion failures from the percentage of crack length with little or no distress conditions. The shaded materials shown below at the Yankton test site were not chip sealed and revised metrics were used for the exposed sealant materials.

Highmore	CSI	Yankton	CSI
Roadsaver 522	1.3	3405M	1.6
Deery 101SD	0.3	MacSeal 6690	0.9
Mod 4 3405	0.1	Mod 4 3405	0.6
3405 M	0.1	Elastoflex 72	0.6
MacSeal 6690	0	Roadsaver 522	0.5
Deery 101ELT	-0.1	Deery 101SD	0.4
Roadsaver 231SD	-0.2	Roadsaver 231SD	0.1
Elastoflex 72	-0.3	Deery 101ELT	-0.2

12.1.3 ASTM D6690 material specifications and laboratory test results.

- The sealant temperatures measured during installation for Elastoflex 72 and Deery 101ELT at the Highmore site were 30°F and 10°F, respectively cooler than manufacturer recommendations. These installation temperatures may have contributed to the increased percentage of sealant distress as evaluated by the crack sealant index.
- Low installation temperatures for Roadsaver 522 and Mod 4 3405 (15°F and 20°F cooler respectively) at the Yankton site and Deery 101SD at the Highmore site (10°F cooler), however, appears to have had less influence on the sealant performance, as rated by the crack sealant index.
- Low resilience measurements reported by the SDDOT materials lab did not seem to affect the better performance of Roadsaver 522 at the Highmore site, however low resilience measurements for Elastoflex 72 and Deery 101ELT may have contributed to the poor performance at the Highmore and Yankton sites, respectively.
- The contrasting performance of materials at the two test sites with low resilience measurements and pouring temperatures did not follow an observable performance trend.

12.1.4 Crack sealant performance without shoulder chip seal (Yankton site)

- The comparison photographs on the shoulders and the adjacent chip-sealed roadway reveal a more uniformly distributed sealant extension over the routed reservoir width compared with concentrated extensions at the reservoir edges in the chip seal.

12.2 Review of South Dakota's standard specifications for asphalt crack sealants

South Dakota's standard specifications for asphalt crack sealant materials and construction were compared with six neighboring states of Wyoming, Montana, North Dakota, Minnesota, Iowa, and

Nebraska. The specifications are similar for routing, cleaning, sealing, and temperature restrictions. Notable differences include Montana's specification for a routed reservoir dimension of 1.5 in. which is based on Canadian research showing good bond and material extension at low temperatures. Minnesota provides an option to increase the routed reservoir width wider than ¾ in., but guidance or requirements are not provided. South Dakota requires humidity to be less than 75%, but this recently added specification has not been in place long enough to assess its effectiveness at improving crack sealant performance.

12.3 Review of South Dakota's approved products list (APL)

South Dakota's evaluation process to include new materials to the Approved Products List is similar to other states. One item from Minnesota's submittal package that could be more specifically included on South Dakota's evaluation request form would be a list of other State DOT's that include a crack sealant material on their qualified products list. A second opportunity to strengthen SDDOT's approved product list would be to include language similar to Minnesota and Montana related to a change in product formulation, requiring reapproval. This addition could clarify the differences between the sealant Deery 101 and Roadsaver 231 which are currently on SDDOT's APL with the products Deery 101ELT, Deery 101SD, and Roadsaver 231SD which were evaluated as part of this investigation.

12.4 Future research

The following two future research projects would extend the benefits of the results and findings of the current investigation.

- Implement a field investigation where chip sealing maintenance is delayed, to determine the length of time a crack sealant is effective as a stand-alone treatment.
- Investigate reservoir widths of 1 in. and 1.25 in. (ratios 1.33:1, 1.67:1) to confirm the potential improved sealant performance applies to South Dakota's crack sealant operations.
- Future research should also determine the best performing crack sealant for a delayed chip seal, as only three of the eight sealants in this investigation were assessed for the entire 84ft length after only 1.5 years without a chip seal.

13.0 RECOMMENDATIONS

13.1 Addition of crack sealant materials to South Dakota's APL.

The relatively high performing crack sealants identified in this research should be reviewed and added to South Dakota's approved product list. Viable sealants for future crack sealing maintenance operations are shown below. The shaded sealants are currently included on South Dakota's APL.

Highmore	CSI	Yankton	CSI
Roadsaver 522	1.3	3405M	1.6
Deery 101SD	0.3	MacSeal 6690	0.9
Mod 4 3405	0.1	Mod 4 3405	0.6
3405 M	0.1	Elastoflex 72	0.6
MacSeal 6690	0	Roadsaver 522	0.5
Deery 101ELT	-0.1	Deery 101SD	0.4
Roadsaver 231SD	-0.2	Roadsaver 231SD	0.1
Elastoflex 72	-0.3	Deery 101ELT	-0.2

13.2 Standard specification for routed reservoir width

Evaluate a wider routed reservoir dimension (1 in. or 1.25 in.) than the current 0.75 in. specification. Wider routing configurations have been shown to improve sealant extendibility for low temperature applications. The benefits of increasing the reservoir width in South Dakota, however, might be limited because of chip sealing activities that are typically performed the summer following crack sealant installation.

13.3 Timing of chip-sealing maintenance

Evaluate a delayed chip-sealing maintenance schedule. The performance of many of the sealants evaluated in this investigation would continue to protect the pavement during this extended time without a chip seal, thereby potentially extending the pavement life through delayed chip sealing maintenance.

13.4 Approved Products List evaluation request form - other State DOT history

Modify the materials evaluation request form to specify which states are currently using a material, testing the material, and include the material on their approved product list. This additional and more specific information enables the Department to more clearly interpret the recent performance history of the material.

13.5 Approved Products List evaluation request form - requalification requirement.

Include language in the APL that requires a requalification for any changes in formulation, manufacturing process, or manufacturing of materials. This addition would clarify the differences between crack sealant materials Deery 101 and Roadsaver 231, which are currently on SDDOT's APL with products Deery 101ELT, Deery 101SD and Roadsaver 231SD which were evaluated as part of this investigation.

14.0 RESEARCH BENEFITS

This project has 1) evaluated eight different crack sealants at two test sites in South Dakota, 2) reviewed South Dakota's crack sealant construction specifications, and 3) assessed South Dakota's procedures for adding or removing crack sealant materials to the approved product list. Benefits realized through the completed research and implementation of results include:

- Improved serviceability and public perception of the condition of South Dakota's roads. Mitigating future damage by increasing the effectiveness of crack sealants will contribute to a safe and smooth driving surface for the traveling public.
- Longer lasting roads— less water infiltration into cracks in the pavement will reduce the potential for accelerated damage, thereby increasing the service life of the pavement. Overall, this maintenance will result in reduced costs to state transportation agencies.
- Roads where improved crack sealing efforts are implemented will experience lower maintenance and rehabilitation costs in the future.
- Analysis of future crack sealant performance data by the SDDOT with evaluation methods developed in this research can be used to confirm the benefits of the improved crack sealing program over time.

15.0 REFERENCES

AASHTO NTPEP (2016) American Association of State Highway Transportation Officials National Transportation Product Evaluation Program, “Project Work Plan for NTPEP Evaluation of Hot Mix Asphalt Crack Sealing and Filling Materials,” AASHTO Designation: CS-16.

AASHTO NTPEP (2009) American Association of State Highway Transportation Officials National Transportation Product Evaluation Program, Final Report of Field and Laboratory Evaluation of Hot-Mix Asphalt Crack Sealing Materials, 2005 Minnesota US 169 Test Deck, NTPEP Report No. 16002.3.

Alberta (2010) Government of Alberta Transportation, “Standard Specifications for Highway Maintenance, §53.4, pp. 5-7.

Al-Qadi, I. L., Masson, J. F., Yand, S. H., Fini, E., and McGhee, K. K. (2009) “Development of Performance-Based Guidelines for Selection of Bituminous-Based Hot-Poured Pavement Crack Sealant: An Executive Summary Report,” Virginia Transportation Research Council, FHWA-VTRC 09-CR7.

Bae, A., Stoffels, S., Clyne, T., Worel, B., and Chehab, G.R. (2007) Direct Effects of Thermal Cracks on Pavement Roughness, *Journal of the Association of Asphalt Paving Technologists*, Vol. 76, pp. 59-68.

BC MTI (2016) British Columbia Ministry of Transportation and Infrastructure, “Standard Specifications for Highway Construction,” §536.

CDOT (2011), Colorado Department of Transportation, “Standard Specifications for Road and Bridge Construction,” §408 pp. 308-309.

Chong, G. J. (1990) Rout and Seal Cracks in Flexible Pavement—A Cost-Effective Preventative Maintenance Procedure, *Transportation Research Record: Journal of the Transportation Research Board*, No. 1268, Transportation Research Board, Washington, D.C. pp. 8-16.

Cuelho, E. and R. B. Freeman. (2004) “Cost-Effectiveness of Crack Sealing Materials and Techniques for Asphalt Pavements,” Final report for the Montana Department of Transportation, Report No. FHWA/MT-04-006/8127.

Decker, D. (2014) “Best Practices for Crack Treatments for Asphalt Pavements,” National Cooperative Highway Research Program, Transportation Research Board, NCHRP Report 784, Washington, D.C.

Erickson, D. (1992) Crack Sealing: Effectiveness, Washington State Department of Transportation, Final Report, Report No. WA-RD 256.1.

Filice, J. (2003), “Study of Crack Sealant Products (Routing and Sealing),” ABRT/RD/TM-05/02, Alberta Transportation, Edmonton, Alberta, Canada.

Fer, E., and Kavanagh, L. (2006) “2004–2006 Joint and Crack Sealant Evaluation Report,” Manitoba Transportation and Government Service, Materials Engineering Branch.

FHWA (1999) Federal Highway Administration, “Sealing and Filling Cracks in Asphalt Pavements,” U.S. Department of Transportation, FHWA-RD-99-176.

FHWA (2001) Federal Highway Administration, “Crack Seal Application Checklist,” Pavement Preservation Checklist Series.

Gnatenko, R., Tsyrkunova, K., and Zhdanyuk, V. (2016) “Technological sides of crack sealing in asphalt pavements.” Transportation Research Procedia, 14, 804-810.

Hall, K.T., Correa, C.E., and Simpson, A.L. (2003) Performance of Flexible Pavement Maintenance Treatments in the Long Term Pavement Performance SPS-3 Experiment, *Transportation Research Record: Journal of the Transportation Research Board*, No. 1823, pp. 47-54.

Hand, A.J., Galal, K.A., Ward, D.R. and Fang, C. (2000) Cost-Effectiveness of Join and Crack Sealing: Synthesis and Practice, *Journal of Transportation Engineering*, Vol. 126, No. 6, Nov/Dec.

Khuri, M. F. and Tons, E. (1992) “Comparing Rectangular and Trapezoidal Seals Using the Finite Element Method,” Transportation Research Record 1334, Transportation Research Board, Washington, D.C., pp. 25-37.

Li, F. and Li, T. (2015) “Field Investigation and Laboratory Evaluation of Asphalt Pavement Crack Seal Band,” *Journal f Testing and Evaluation*, Vol. 43, No. 1, pp. 123-132.

Masson, J.-F., Collins, P., Bundalo-Perc, S., Woods J.R., and Al-Qadi, I. (2005) Variations in Composition and Rheology of Bituminous Crack Sealants for Pavement Maintenance, *Transportation Research Record: Journal of the Transportation Research Board*, No. 1933, Washington, DC., pp. 107-112.

Masson, J.-F., Boudreau, S., and Girard, C. (2003) “Guidelines for Sealing and Filling Cracks in Asphalt Concrete Pavement: A Best Practice by the National Guide to Sustainable Municipal Infrastructure,” Federation of Canadian Municipalities and National Research Council, Canada.

Masson, J. F., and Lacasse, M. A. (1999) Effect of Hot-Air Lance on Crack Sealant Adhesion, *Journal of Transportation Engineering*, Vol. 125, No. 4, pp. 357-363.

Masson, J. F., Lauzier, C., Collins, P., and Lacasse, M. A. (1998) Sealant Degradation during Crack Sealing of Pavements, *Journal of Materials in Civil Engineering*, Vol. 10, No. 4, pp. 250-255.

Masson, J. F., Collins, P., Perraton, D., & Al-Qadi, I. (2007) Rapid assessment of the tracking resistance of bituminous crack sealants, *Canadian Journal of Civil Engineering*, 34(1), pp. 126-131.

McGraw, J.W. and Olson, J. (2007) “Evaluating Minnesota Crack Sealants by Modified Bending Beam Rheometer Procedure.” TRB 86th Annual Meeting Compendium of Papers. 07-1812. Transportation Research Board, Washington, DC.

MDT (2014) Montana Department of Transportation, “Standard Specifications for Road and Bridge Construction,” §403, pp. 193-194.

MDT (2001) Montana Department of Transportation, Maintenance Crack Seal Manual.

MnDOT (2016) Minnesota Department of Transportation, “Standard Specifications for Construction,” §3702, pp. 624-628.

NDOR (2007) Nebraska Department of Roads, "Standard Specifications for Highway Construction," §519, pp. 356-358.

NDOR (2002) Nebraska Department of Roads. Pavement Maintenance Manual www.transportation.nebraska.gov/docs/pavement.pdf.

NHDOT (2016) State of New Hampshire Department of Transportation, "Standard Specifications for Road and Bridge Construction," §413.

NYDOT (2013) New York Department of Transportation, "Special Specifications," §412.

OPSS (2015) Ontario Provincial Standard Specification, "Construction Specification for Routing and Sealing Cracks in Hot Mix Asphalt Pavement." §341

Peshkin, D.G., Hoerner, T.E., and Zimmerman, K.A. (2004) "Optimal Timing of Pavement Preventative Maintenance Applications," Report 523, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C.

Ponniah, J., and Kennepohl, G.J. (1996) Crack Sealing in Flexible Pavements: A Life Cycle Cost Analysis, *Transportation Research Record: Journal of the Transportation Research Board,* No. 1529, Washington, D.C., pp. 86-94.

Ragab, M., Waldenmaier, A.J. and Abdelrahaman, M. (2013) "Asphalt Pavement Thermal Crack Maintenance Best Management Practices: Survey and Literature Review," Final report to the North Dakota Department of Transportation, Report No. SPR-R034(009).

Rajagopal, A. (2011) "Effectiveness of Crack Sealing on Pavement Serviceability and Life," Final report for the Ohio Department of Transportation, FHWA/OH-2011/14, Columbus, OH.

Ram, P. V., and Peshkin, D. G. (2014) Performance and Benefits of Michigan DOT's Capital Preventive Maintenance Program, *Transportation Research Record: Journal of the Transportation Research Board*, No. 2431, Washington, D.C., pp. 24-32.

SDDOT (2015) South Dakota Department of Transportation, "Standard Specifications for Roads and Bridges." §350, pp. 181 – 184

Shuler, S. and Hessling, J. (2011) Elevation, Deicer Impacts Crack Sealant Performance, *Pavement Preservation Journal*, Naylor, LLC. Gainesville, FL.

Shuler, S. and Ranieri, V. (2009) A Study of the Performance of Six Crack Seal Installation Procedures, *Sixth International Conference on Maintenance and Rehabilitation of Pavements and Technological Control (MAIREPAV6)*. Politecnico di Torino, Turin, Italy.

Shuler, S. (2010a) "Evaluation of the Performance, Cost-Effectiveness, and Timing of Various Pavement Preservation Treatments," CDOT-2010-3, Colorado Department of Transportation, Denver, CO.

Shuler, S. (2010b) "An Apparent Healing Mechanism in Asphalt-Based Crack Sealants." TRB 89th Annual Meeting Compendium of Papers, 10-2525. Transportation Research Board, Washington, DC.

Shuler, S. (2009) Short-Term Crack Sealant Performance of Three Crack Sealants in Three Climates Using Several Installation Techniques, TRB 88th Annual Meeting Compendium of Papers, 09-0689, Transportation Research Board, Washington, DC.

Smith, K.L., and Romine, A.R. (1999) “LTPP Pavement Maintenance Materials: SHRP Crack Treatment Experiment, Final Report,” FHWA-RD-99-143, Federal Highway Administration, Washington, D.C.

Soliman, H.; Shalaby, A.; and Kavanagh, L. (2008) Performance Evaluation of Joint and Crack Sealants in Cold Climates Using DSR and BBR Tests, *Journal of Materials in Civil Engineering*, Vol. 20, No. 7. American Society of Civil Engineers, Reston, VA. pp. 470-477.

Truschke, C., Peshkin, D., Smith, K.L., Smith K.D. (2014) “Colorado Department of Transportation Hot Mix Asphalt Crack Sealing and Filling Best Practice Guidelines,” Colorado Department of Transportation, Report No. CDOT-2014-13.

Wilde, W.J., and Johnson, E.N. (2009) Effect of Crack Sealant Material and Reservoir Geometry on Surface Roughness of Bituminous Overlays, *Transportation Research Record: Journal of the Transportation Research Board*, No. 2108, Washington, D.C., pp. 69-74.

WYDOT (2010) Wyoming Department of Transportation, Standard Specifications for Road and Bridge Construction, §403, pp. 307-319.

Yang, S.-H.., Al-Qadi, I., McGraw, J., Masson, J.-F., and McGhee, K.M. (2010) Threshold Identification and Field Validation of Performance-Based Guidelines to Select Hot-Poured Crack Sealants, *Transportation Research Record: Journal of the Transportation Research Board*, No. 2150, Washington, DC. pp. 87-95.

Yildirim, Y., Korkmaz, A., and Prozzi, J. (2006) “Performance Comparison of Hot Rubber Crack Sealants to Emulsified Asphalt Crack Sealants,” FHWA/TX-06/0-4061-3, Center for Transportation Research, University of Texas at Austin.

Yildirim, Y., Qatun, A., and Kennedy, T.W. (2003) “Performance Evaluation of Hot and Cold Pour Crack Sealing Treatments,” Project Report for the Texas Department of Transportation, FHWA/TX-03-4061-2.

Yildirim, Y., Yurttas Y., and Boz I. (2010) “Service Life of Crack Sealants,” First International Conference on Pavement Preservation, Paper No. 19, California Department of Transportation, Federal Highway Administration, Foundation for Pavement Preservation. Washington, D.C., pp. 377-392.

Zinke, S., Hogge, B., O’Brien, C., Mahoney, J. (2005) “Evaluation of Pavement Crack Treatments Literature Review, Final Report for the Connecticut Department of Transportation, CT-2241-F-05-6.

APPENDIX A OUTLINE OF SAMPLE QUALITY CONTROL MEASURES FROM FHWA (2001)

- Surface Preparation
  - The surface is clean and dry.
  - Other pavement distresses have been repaired.
- Weather Requirements
  - Review manufacturer installation instructions for requirements specific to sealant use is completed.
  - Ambient and/or surface temperature meet manufacturer and all agency requirements for routing and sealing.
  - Sealing does not proceed if rain is imminent.
  - Application does not proceed if there is any moisture on the surface or in the crack.
- Routing
  - Routed reservoir is checked for correct configuration (width and depth).
  - The asphalt concrete mixture is in sound enough condition to produce the required reservoir configuration without excessive spalling of the pavement during cutting.
  - The cut reservoir is centered over the crack and cutting of both sides of the crack back to sound pavement has occurred.
- Crack Cleaning (Air Blowing)
  - Dirt and debris are blown from the crack. Dirt has not been blown from one crack to another that has already been cleaned. All dirt and debris is blown off the roadway.
  - Check is conducted for moisture in the crack and along the reservoir's sidewalls. If moisture is found, necessary steps are taken to remove the moisture.
- Hot Air Blasting
  - Hot air blasting is conducted immediately ahead of hot applied sealant installation to minimize condensation formation prior to sealant and to maintain warm temperature.
- Sealant Application
  - Manufacturer's and agency's temperature installation requirements are being followed.
  - Melter hear transfer medium is heated to the correct temperature range.
  - Sealant is heated to a minimum of the manufacturer's recommended temperature, but temperature does not exceed the material's safe heating temperature.
  - Sealant is continuously agitated to assure uniformity, except when adding additional material.

- Operator is wearing required personal protective equipment.
- If the melter is equipped with a heated hose system, the hose is heated to operating temperature prior to beginning sealant application.
- If melter does not have a heated hose, the hose if verified to be unplugged and clear prior to beginning application.
- Sealant in recirculated through the hose to warm the hose prior to application. During idle periods, or if it is noted that sealant is cooling through the hose, sealant is recirculated through the hose back into the material vat to maintain hose temperature.
- Sealant temperature is checked periodically to assure proper temperatures.
- Melting vat is kept at least one third fill to help maintain temperature uniformity.
- Crack channel/reservoir is filled from the bottom up, to the specified level.
- Sealant material is formed/squeegeed/finished (if required) to the specified configuration.
- Sufficient material is applied to form the specified configuration, but not so much as to oversupply squeegee.
- Surface Band-Aid applications (if required) are within the specified thickness and width.
- De-tackifier or other blotter is applied to reduce tack prior to opening to traffic, if needed.
- Any sealant overband is centered over the crack.
- Sealant is reapplied to low areas where sealant has settled or where too little material was applied.
- Adhesion is checked by pulling up cooled sealant. Unbonded sealant is removed and crack is resealed.

- Common Problems and Solutions
  - Sealant not adhering to crack:
    - Crack not clean enough; Re-clean.
    - Wet cracks; Allow to dry, or use heat lance.
    - Low sealant application temperature; Verify temperature gauges on melter, heat to correct temperature.
    - Cold ambient temperature; Allow temperature to rise, or use heat lance.
  - Sealant cracking or debonding in winter:
    - Sealant to stiff; Use softer grade.
    - Excessive pavement distress
    - Poor cleaning during installation; Improve cleaning.
    - Not providing a widened reservoir; Use a widened reservoir configuration.

        - Snowplows pulling out sealant; Apply sealant flush with pavement.
        - Sealant installed too deep in crack; Use correct depth to width ratio.
    - Sealant pick-up when opened to traffic
        - Opened traffic too soon after application; Delay opening.
        - Crack not clean and/or dry; Re-clean or dry.
        - High ambient temperature; Seal in cooler temperatures.
        - Excessive sealant application; Apply flush with surface.
        - Sealant too soft for the climate; Use a stiffer sealant.
        - Use a detackified or blotter to reduce initial tack.
        - Overheated or underheated sealant install at correct temperature; Check temperature gauges on melter.
        - Sealant contaminated with solvent or heat transfer oil from tank leak.
    - Sealant gelling in melter
        - Overheated sealant; Check melter temperature gauges.
        - Sealant reheated too many times; Use fresh sealant.
        - Use of sealant with short pot life; Use sealant with longer pot life.
    - Bumps in asphalt concrete overlays; Sealant adhering to overlay and interrupting shoving during mix compaction
        - Excessive sealant applications on surface; Use recessed or surface flushed sealant application.
        - Seal at least one year prior to overlay
        - Apply detackifier or blotter to reduce sealant adhesion to overlay.
        - Use of a pneumatic rubber tire roller as the breakdown roller does not tend to shove the mix during compaction. Selection of roller type is especially critical for thin hot mix overlays.
        - Use stiffer tack coat, (FHWA, 2001)

APPENDIX B INTERVIEW QUESTIONS AND SUMMARY OF RESPONSES

Interview Questions:

1. Familiarity with various materials and/or techniques associated with crack sealing in general
    - Please tell me what you know about crack sealing in general, for example:
        - Process
        - Timing
        - Material selection
        - Requirements
        - Materials
        - Conditions
        - Cracks
        - Laboratory tests
        - Construction
        - Testing
        - Performance
        - Pavement engineering

2. Experience with crack sealing in South Dakota
    - What is your part in the crack sealing maintenance efforts in SD?
    - Please describe the crack sealing program within SD.
        - What materials and technique combinations are used to address transverse cracking in asphalt pavements?
        - How do you determine which roads, or when in their life, they are crack sealed?
        - What kinds of laboratory tests do you conduct to verify the material properties of crack sealant products?
        - How do you schedule crack sealing after construction of a new pavement or overlay?
        - Describe the process that is used to seal cracks on asphalt pavements in SD.
        - What time of year is crack sealing generally done?
        - How are cracks prepared prior to sealing?
        - What about crack widths? Minimum? Maximum?
        - Air temperature? Pavement temperature?
        - What about rainfall and/or moisture concerns?

3. Familiarity with specifications and/or guidance procedures
    - How familiar are you with the specifications and/or guidance procedures associated with crack sealing of asphalt pavements in South Dakota?
    - Do you know how the specifications for crack sealant were developed for South Dakota?
        - Do you have any suggested changes to these requirements based on your experience?
    - How are crack sealants approved for use?
        - Are you familiar with the ASTM D6690 Type IV specifications? If so, do you have any comments on them?
    - Are any material acceptance tests beyond ASTM D6690 Type IV ever used? If so, please describe.
    - Describe the bidding process for crack sealing?

4. Identification of problems or challenges
    - Describe any problems or challenges that you or the department has faced with respect to crack sealing of pavements in South Dakota?
    - Have you experienced a decline in the performance of crack sealants in time?
        - If so, what do you think is causing this?
        - If not, what things are being done well that results in good performance of crack sealants?
5. Qualitative assessment of crack sealing practices within SDDOT
    - Are any formal programs in place to evaluate the performance of crack sealants in South Dakota? If so, please describe frequency, timing, data collection during these evaluations.
    - How are sealant failures defined?
    - How long do you estimate crack sealants last, based on your experience?
    - What materials and/or techniques have worked well for crack sealing transverse cracks on asphalt pavements?
    - How does crack severity come into play in crack sealing operations in South Dakota?
    - How do you determine when crack sealant should be replaced?
    - Do you know what effect crack sealing has on the life of the pavement?
    - Has any consideration been given regarding the use of different materials at different times or for different kinds of cracks, etc.?
6. Ideas for improving crack sealing practices
    - How long do you think crack sealant on asphalt highways should last?
    - Any suggestions on how to improve crack sealing performance?
    - Do you think there should be special procedures for crack sealants applied before another preventive maintenance treatment (fog seal, chip seal, etc.)?
7. Anecdoal data from field evaluations
    - Do you have any data to share regarding crack sealing of pavements in South Dakota? Do you take samples from the field to verify that the material met the required specifications?
    - Are field acceptance tests done on crack sealing? If so, what do these entail?

<u>Detailed Interview Notes:</u>

Clarence Bowman – Highway Maintenance Area Supervisor, SW region (January 17, 2017)

- Responsibilities generally entail all facets of maintenance, but in terms of crack sealing he checks when the sealing needs to be done and then runs maintenance crews to do the sealing
- Usually does the work in Feb/March timeframe
- Indicated that crack sealing has become more aggressive recently – i.e., making sure cracks are sealed on a regular time schedule without too many delays
- Uses pre-approved products (thinks it’s Crafco brand most of the time), hot pour
- Gets it in Styrofoam boxes to reduce waste and for ease of handling
- Squeegees the sealant to form overbands on either side
- Uses toilet paper as blotter material
- Uses backer rods when the crack is too deep and/or wide to save material

- Doesn't rout cracks so materials are applied using band-aid technique
- Indicates that he believes this method works well and has shown good performance
- Have issues if crew tries to move too fast, not allowing the sealant to flow down into the crack and thereby creating a recessed fill which don't seem to perform as well as the flush
- Applies sealant all the way to the shoulder rather than leaving the last approximately 1 ft. unsealed
- Maintains their own kettle for heating the material
    - Wand is unheated
    - Current equipment is approximately 17 years old.
- Does annual inspection of roads with lead workers
- Crack sealing in town wasn't done near a highway that had been crack sealed and he commented that there is a definite difference in pavement quality
- Doesn't seem much difference in performance between the contracted crack sealing and the maintenance crack sealing
- Generally seal cracks 1 year prior to chip sealing
- Sees more reflective cracks coming through the hot mixes than through chip seals
- Generally seals cracks that are ¼ to ½ in. wide.
- Has seen local bulging of overlays around crack sealed areas if the crack sealant is too thick and/or wide.

Jim Hyde – Pierre Regional Operations Manager (Dec. 21, 2016)

- Close to 30 years of experience
- In Maintenance for the past 10 to 12 years
- In December would go around to quantify cracks to estimate quantities of material needed to seal cracks
- Typically seal 2 to 3 years after paving during spring or fall using a contractor and 3405M product
    - Routed ¾" x ¾" reservoir
    - Hot pour with toilet paper as blotter material
- Sometimes would get total failure by the next winter.
- Noticed one time that after it rained the crack sealant turned into a sticky gel and created a disaster
- Pavement expands in winter but sealant doesn't seem to expand well
- One region tried to rout to 3/8" by 3/8" but the reservoir was too narrow to be practical
- When Jim moved to maintenance the crew would reseal and/or seal cracks in February when the cracks were at their widest
    - Used a crumb rubber product (name?)
    - Filled flush but the end result after the material cooled was a slightly recessed seal
    - There was no overband
- Material was placed before second chip seal
    - Year 1 – overlay pavement
    - Year 2 to 3 – first crack seal during spring or fall using 3405M product
    - Year 3 – first chip seal
    - Year 8 to 9 – second crack seal during winter using crumb rubber product

  - Year 10 – second chip seal
- Material didn't push up when warm even though the pavement expanded
- If 3405M was used in the winter then it would have pushed up above surface of road
- Sees a need for both products
- Can't rout the soft materials because it gums up the router
- Move toward more recycled asphalt millings in mix designs may be causing greater number of cracks and more brittle pavement
  - This seems to be working well and
- Unsealed cracks do not perform well
  - Crack widths in the winter can be up to 1 ½" wide
  - Secondary cracking near original crack, joint fractures and eventual collapse of the area in the crack zone
- When the chip oil is sprayed during chip sealing, the crack sealant is rejuvenated making it more gummy

Brett Meadors – Highway Improvement Crack Sealing Contractor (January 3, 2017)

- Been working in crack sealing for 16-17 years
- Done other work related to pavement maintenance (mastics, joint sealing, some concrete sealing)
- Primarily works in SD but also has done work in NE and WY. Lesser extent in IA and MT
- Estimates that he does about 70% of the crack sealing in SD
- Believes that the SDDOT needs to revamp their crack sealing procedures and specifications to get better results in the field
- Brett seems to like the ¾ x ¾ rout pattern, but does not like the 5/8 x 5/8. Thinks there should be no reason to rout differently in different regions throughout the state
- Likes the use of the overband 1-3" on each side of the crack
- Increased humidity near the southeastern side of the state; he believes this has an influence on the performance
- Thinks that longitudinal joints should also be filled; seemed to indicate that in some parts of the state these are not sealed
- There needs to be increased education on crack sealing; Brett gives presentations to help others understand the importance of crack sealing and provide practical information
- Does not like the narrow and deep rout configuration (used in WY)
- Also doesn't understand the need for backer rods
- Thinks that the influence of the pavement mix design should be considered with respect to crack sealing
- He believes that the maintenance crack sealing efforts should be done in general accordance with the specifications to get better results
- If pavements are older and the oils are more brittle, etc. then perhaps the sealant and/or procedure needs to reflect that to get the best performance
- Routing exposes the better oils inside the pavement that haven't been oxidized and therefore provides a better surface for the crack sealants to bond to
- Thinks taking samples from out of the kettle (what SD currently does) is better than taking a virgin block from the pallet to be used for laboratory purposes

- Suggested that compatibility with asphalt should be done to ensure good bond
- Suggested that inspections be done to ensure proper installation
  - Making sure the rout is on the crack
  - Ensuring proper depth of rout
- Granite in the west, quartzite in the east
  - Perhaps the differences between these may cause bonding issues
  - Quartzite seems to have more difficulty sticking to oil
  - Quartzite is very hard
  - Some crack sealants can add antistripping agents to ensure good adhesion
  - Routers are impact routers and not saws
- Thinks that the eastern side of the state has more issues and should perhaps dictate what the remainder of the state should do
  - Eastern side is more sensitive
- Believes crack sealing should last 3-5 years
- Currently crack seal after paving but before chip seal
  - Any new cracks that show up after chip seal should be routed and filled like before – no band-aid
  - Pull out older crack seal and replace if necessary
- Keeping water out of pavement structure is important
- Has experienced chip seals holding water in the road
  - Highway 11 north of I-90
  - Sealing done in fall
- Air blowing does a good job most of the time
  - Compressed air can lift chip seal if not careful (floating chip seal)
  - More likely on older chip seals
- Hot lance is used occasionally but should be used with care because the heat can easily damage the pavement
  - 1400 F
  - Can attract moisture on medium cold days
- Thinks the humidity spec is good as it restricts sealing when humidity is too high
- Manufacturers are doing a pretty good job but is not sure what makes good sealant
  - Knows which products work well
  - Has good relationships with many manufacturers
- Has used products from
  - Deery
  - Crafco
  - Maxwell
  - WR Meadows
  - McAsphalt
- Tends to think that the more expensive products work a little better (most of the time)

Rick Rowen – Bituminous Engineer (Dec. 21, 2016)

- Worked with crack sealing since around 2001
- Crack sealing was historically taken care of by maintenance, but staff changes and other internal workings required that Rick get involved
- He is in charge of testing the crack sealant materials for SD

- Samples are taken directly from the hot kettle as the contractor is installing the sealant
    - This seems to provide more accurate data as to what is being put down on the road
    - Failures of some of the requirements is more evident when this sampling method is used when compared to receiving a virgin box of material that hasn't been heated in the contractor's kettle
- There doesn't seem to be a good inspection program in place – mostly ad hoc
- Rick has been involved mostly in lab work and not field work although there are some times when he has been asked to come out to a job to review things
- Pavement design has changed over the years
    - Seems to be content with PG grading and asphalt design
    - Senses that there are less cracks with the modified asphalt overlays than before
- Would like to see whether there are any other tests that may be more relevant or associated with better performance of crack sealing
- Would like to entertain a bond test that utilizes the asphalt materials from SD rather than two concrete pieces to see the difference. Also desired a better compatibility test.
- Indicated that McAsphalt said it could modify its crack sealant to be more compatible with higher quantity of quartzite in some regions of SD
- Routing is ¾" x ¾" but routing can at times be pretty hard on the pavement. Thought to cause spalling of materials that may affect bond.
- Recently made changes to the specification to restrict installation of crack sealants during summer (hottest) months. This change was based on information from other northern states (Minnesota).
- Hasn't necessarily seen a decline in the performance of crack sealants over time, but indicated that there is always room for improvement
- Assessments are made using existing tools or methods developed by others (e.g., NTPEP, MnRoad, other northern states)
- It is difficult to see the failures since crack sealants are obscured by chip seals within one to two years.
- Like to see crack sealant materials last 5 to 7 years
- Believes that even crack sealants that are showing some deterioration are keeping much of the water out of the pavement
- Working well means that there are no secondary failures occurring in the cracked area, such as secondary cracking, cupping or raveling
- Procedure
    - First crack sealing begins with a contracted seal 1 to 2 years after a new pavement or overlay.
    - Chip seal follows that by 1 to 2 years
    - Crack sealing pavements that have re-cracked or any new cracks since the first crack sealing operation is done on an ad hoc basis
    - Crack sealing becomes a maintenance activity at that point and is done in house with maintenance crews during the winter.
    - Contracting out the second crack sealing is rare
- Recalls one time on I-90 where a crack sealing job was overlooked or didn't occur for some reason and the joints deteriorated faster, raveling and debonding was present

- Convinced that crack sealing is necessary to ensure longevity of pavements

Jerry Schaefer – Certification Engineer SDDOT (Dec. 20, 2016)

- Maintains the list of approved products but is not the one that determines whether or not a product is included on the list
- In the past, worked 18 years as lab technician testing products for crack sealing purposes
- Also did inspection work during crack seal installations
  - Monitored temperatures, vessel heating compliance, installation procedures, etc.
- During that time they would set up ad hoc test sections in SD and evaluated for 2 to 3 year timeframe
- This process was used to determine whether materials were able to make it on the approved products list
- No formalized process for approval of these products, but one is needed
  - Lay down test sections
  - Document quality of construction
  - Compare with control (usually a material that has good past performance and has been on the APL for a while)
- Recalls one particular test section that he and Dan Vockrodt worked on together near Hitchcock, SD near Pierre
  - Materials did not perform well
  - Many adhesion and cohesion failures in the first winter after installation
  - Chip seal was installed the following spring which obscured cracks
  - Not sure why these materials performed poorly
  - Installation was good and done according to the specification
- Need better guidance on what constitutes good/poor performance
- Typical to install crack sealant with a wand and horseshoe-shaped squeegee to create a flush fill with 1 to 2 inch overband on both sides of the crack. Toilet paper is used as a blotter.
- Crack sealant is typically installed on new pavement
- Testing for QC purposes:
  - Collect one box of sealant from each lot (may be more than one lot per job depending on the size)
  - Report results of lab tests back to field engineer who determines the next course of action based on results
  - Crack sealing is already installed by the time the results of the tests are determined
  - Need better guidance on the deduction for materials that don't meet spec
- General feeling that the lab tests used to determine product performance aren't working as well as they used to in the past
- May need new specifications or updated testing requirements that more accurately relate to better performing materials in the field
- Asphalt mix designs have changed
- Familiar with NTPEP program
- Another database is the APEL
  - Seems useful but need to determine whether it will work for SD

Gregg Ulmer – Highway Maintenance Supervisor, near Winner, SD (Dec. 21, 2016)

- 26 years at SDDOT
  - Began in maintenance
  - Became lead
  - Been a supervisor since 2009
- The majority of crack sealing is done during the winter
- This is a maintenance activity to address newly formed cracks that are present since the chip seal was installed and reflective cracking of old cracks
- No routing, just a band-aid application over the raw crack
- Usually done in January/February timeframe, done by March
- Blow out cracks with air compressor
- Use own kettles
- Obtain materials through regular bidding process
- Usually use a crumb rubber material (thought to be a Crafco or Deery product)
- Seems to show good performance
- Overband of 1 to 3 inches on both sides of the crack
- Manufacturer specs are followed when heating and applying the materials
- Expansion of the pavement in the summer pushes the crack sealant up but it gets ironed out – not much tracking and little to no pullout
- Sometimes during spring and the roads are thawing, water will infiltrate up from below and through the crack sealant
- Believes that these sealants get 4 to 5 years of life, but this difficult to tell because they are oftentimes obscured by chip seals prior to that
- During routine checkups during winter, most of the cracks seem to be performing well meaning that they are still intact and sealed to either side of the crack walls
- Sometimes when performing a patch the hot oil rejuvenates and softens crack sealing rubber, but this has no detrimental long term effect
- Questions the need for routing cracks to make them wider
- Generally satisfied with the performance of crack sealant
- Shared a challenge that occurred several years ago where there was a huge pullout problem on the interstate in the heat of summer
- Considers bonding issues to see whether follow-up is necessary
- A lot of times the second chip seal will be on before crack sealing is needed
- Hasn't conducted any independent side-by-side evaluations

Brian Vandam – Transportation Specialist (Dec. 27, 2016)

- Routing after chip seal works okay but seems like there are more moisture issues
  - On one job recently they needed to use hot lance and go over the routed area twice to get it dry enough to seal
- Has had good experience with heat lance (propane torch) to get the water out, but water may continue coming out if you are thawing the pavement and releasing new frost from the ground
- Need to be careful not to overheat the edges of the routed crack, but Brian doesn't believe it is extremely critical

- Also need to be careful not to blow the crack sealant off from adjacent to the crack. High pressure air can flake off chunks of chip seal if not careful
- Believes that moisture trapped under an in the chip seal is released during heat lancing and air compressor work when cracks are cleaned, but not exactly sure if this is the case.
- May differ in areas that use natural stone versus crushed aggregate for the chips
    - Indicated that bonding may be affected by ionic issues associated with stones – incompatibility
    - Indicated that it also may also be due to moisture trapped in the bituminous chip seal tack
- Hasn't experienced any other issues with routing through chips seals, whether it's one or two layers
- Indicates that there is no reason to rerout a crack that has a chip seal over the originally sealed crack
- Maintenance does use a router as part of their crack sealing process
- Near Sioux Falls the usual process for maintenance goes something like this:
    - Year 1 – crack seal
    - Year 2 – chip seal
    - Year 2-5 or 6 – maintenance does touch up work, usually in the spring and fall (Berum 195 LM is a common product that is used)
    - Year 7 – may let contract to fix remaining cracks if there are enough
    - Year 8 – chip seal #2
    - Years 9-12 or so – touch up maintenance again, and if there are enough near year 14 then they let a contract to have cracks sealed
    - Year 14 – chip seal #3
- Seeing debonding in the first year of active service (sealed in the spring and seeing issues that next winter)
- Areas that have poorer performance are also sensitive to moisture intrusion which has caused cupping and secondary cracking
- Believes that better materials are needed
- In one area on Highway 11 they had a section that was too wet to crack seal in the summer so they didn't get to it. They ended up chip sealing it that next summer without having any of the cracks sealed and there were a lot fewer cracks that propagated up through the chip seal. It was estimated to take 33,000 lb. of crack sealant for the crack sealing job and now, based on a more recent account of the quantity of cracks, this was reduced to around 5,000 lb.
- Using a CRS 2P chip oil.
- Get best performance out of crack seal earlier in the pavement life (fewer chip seals)
- Thinking there may be a better method
    - New pavement
    - Chip seal
    - Crack seal
    - Maintenance touch up
    - Continue
- Thinks that perhaps smaller reservoirs may work on smaller cracks with lower crack density

- Wider routing would make it easier to hit the crack as there are a lot of times when the cracks are missed because the rout trough is too narrow
- Generally thinks that Deery 101 ELT and WR Meadows 3405M products work well

Dean VanDeWiele – Area Manager SDDOT (January 25, 2017)

- Manages one area within the state; there are 12 area managers in SD
- Oversees new construction and all maintenance
- Typically crack seal with construction crew (rout and seal) 2 years after overlay or pavement improvement
- Exact timing is worked out with local planners and management
- Chip seal the year after that
- Second chip seal is 7-10 years after the first chip seal
- Maintenance takes care of subsequent crack sealing work to re-seal anything that's come up since the chip seal
- Fill during winter or early spring when crack is widest
- Doesn't have bulging problems in the summer.
- Only time rout and seal crack sealing takes place is after a more significant pavement rehabilitation or overlay
- Maintenance crack sealing is typically done by blowing the crack out with compressed air and filling. Overband is used by squeegeeing the crack sealant
- Hot-pour sealant is used – whatever is allowed by the APL
- Admits that this method doesn't remove the presence of moisture in and around the crack every time
- Sometimes if there has been significant settlement around the crack, it can be leveled using a mastic then any new cracks that show up after that can be sealed with hot-pour sealant
- Crack sealing always precedes chip sealing
- Dean believes that crack filling works well using a crumb rubber product (McAsphalt product)
- Dean is able to tell when crack sealing works and when it doesn't by how the area around the crack is behaving; if it is subsiding from water inundation and secondary cracking is occurring then the sealing isn't working, but if the pavement around the crack is okay and there are no secondary stresses, then the sealant is working well
- More aware of the benefits of crack sealing now than in the past
- Dean believes that inspection is important during contracted crack sealing installation, but doesn't believe it's necessary during maintenance crack sealing
- Dean believes that the maintenance applied crumb rubber crack sealant works for about 4 to 5 years.
- Believes that crack sealing today is performing similarly to the past although he and others understand the benefits better
- Understands the positive impact crack sealing has on pavement life.
- Also uses crack sealant in longitudinal cracks within the rutted zone to seal out water in these areas

Dan Vockrodt – Operational Maintenance Engineer (Dec. 23, 2016)

- Recently taken a different position but worked as Operations Maintenance Manager
- Been with SDDOT for 25 years
- Has been working toward learning how to improve crack sealing for the past 2 years or so
  - Has done some work looking at what MnDOT has done
  - Helping Ryan Johnson
- Understands the need to have a system to allow and remove materials from the APL depending on how they perform in SD
- Timing
  - Doing crack sealing when it's hot isn't good
  - Doing crack sealing in the winter may have other problems
  - Need to find a happy medium to optimize crack width
- Maintenance crews do crack sealing after cracks reemerge post chip sealing or after multiple new cracks open up
- Dan indicated that he is unsure of exactly what is causing there to be poor performance
  - Many conflicting variables
  - Difficult to pinpoint one thing and it may be a combination of several things
- Believes that the contractors are doing a good job, so that there must be something at play with the technique(s) used during installation or the material itself
- Recognizes that there needs to be more oversight and inspection work done during installation by the contractors
- Dan believes that the frequency of cracks plays into the performance of crack sealant and that roads with better designs and that crack less frequently may see larger movements at the cracks since they are further apart and all the accumulated strain goes into fewer stress relief points. When there are more frequent cracks he has seen that crack sealant works better because there is less movement at each individual joint.
- Sioux Falls area seems to be having the biggest problems
  - This may be related to the mineral type of the aggregates used in the asphalt layer (quartzite), which differs from materials that are predominantly limestone as you move westward across SD
  - Dan wonders is there is a compatibility issue associated with the aggregate mineral type
- Failures are mainly adhesion failures but also some cohesion failures
- As far as he knows the materials used pass the required lab tests
- Understands that moisture issues are important and he is concerned that this may not be being properly addressed during installation, but just doesn't know
- Tried different sized reservoirs (5/8" x 5/8") but didn't work well – too narrow to properly catch the crack, went back to ¾" x ¾"
- Willing to try wider routing techniques if it yields better performance
- Believes it is generally important for maintenance crews to follow the specifications for materials and methods
- Maintenance crews used crumb rubber-based material and install during heart of winter (Feb) when cracks are at their widest

- Admits that some areas in SD may have a different idea of what failure is and may be inadvertently indicating that cracks sealant is working simply because it hasn't been completely removed from the reservoir, rather than adhesion and/or cohesion failures
- Most maintenance-related crack sealing repairs occur after first chip seal, but may fix some cracks prior to the first chip seal
- Specifications were recently changed (within the last year or so) to add provisions for humidity, time of year, etc. Haven't had enough time to thoroughly evaluate the effects of these changes.
- Unit weight is a concern and is the reason for the requirement in the specifications to ensure that companies are not adding other fillers that may negatively affect the performance of their sealants (materials are currently sold by weight)
- Encourages maintenance crews to use materials that fit the specification (i.e., ASTM D6690 Type 4)
- He and others are paying more attention to crack sealing than in the past because of the emphasis on pavement preservation. He isn't sure whether the performance of crack sealing is declining or whether it is just being paid more attention
- Thinks that crack sealing will work much better if the conditions are 100% favorable (good weather, good routing, cleaning, installation, etc.)
- Believes that Minnesota is also experiencing similar challenges
- 3-5 year life of crack sealing is acceptable, but seeing less than 3 most of the time in the field.
- Newer binders in pavements seem to be helping with crack density
- Believes based on experience that crack sealing is necessary and keeps water out.
    - Due to fine-grained soils and sensitive subgrades, keeping water out is important.
    - Sees dipping of cracked area due to water ingress
- Not sure about any interactions between crack sealing and chip sealing
- Field tests were conducted to determine placement of crack sealing products on the Approved Products List (APL)
- Provided Bob Longbons with results of his observations of performance of crack sealants installed mostly around Pierre, SD

APPENDIX C PHOTOS OF CRACK SEALING INSTALLATIONS BY BRIAN VANDAM; 2013, 2014

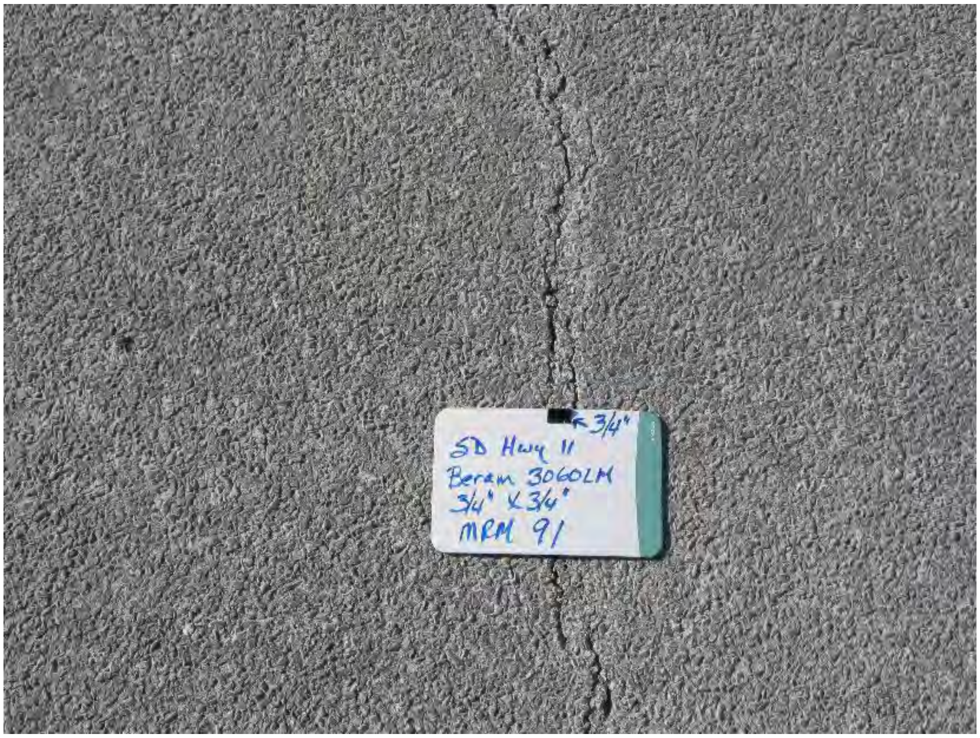


Figure C - 1: Highway 11 MRM 91

Figure C - 2: Highway 11, MRM 92.

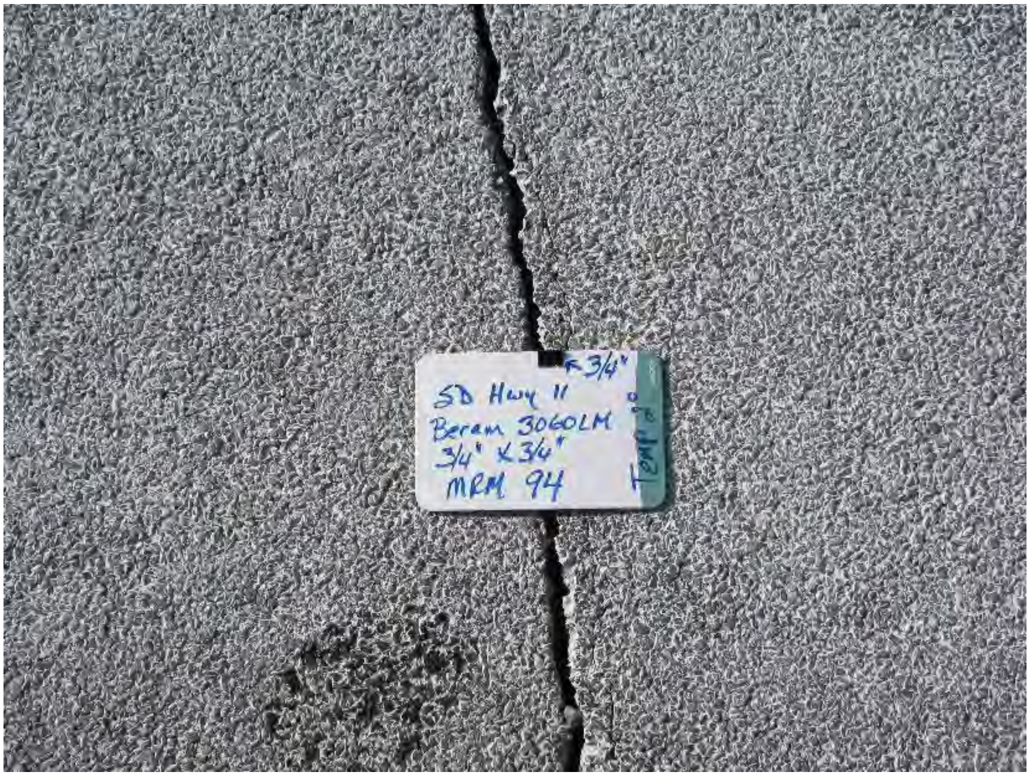


Figure C - 3: Highway 11, MRM 93.

Figure C - 4: Highway 11, MRM 94.

Figure C - 5: Highway 11, MRM 95.

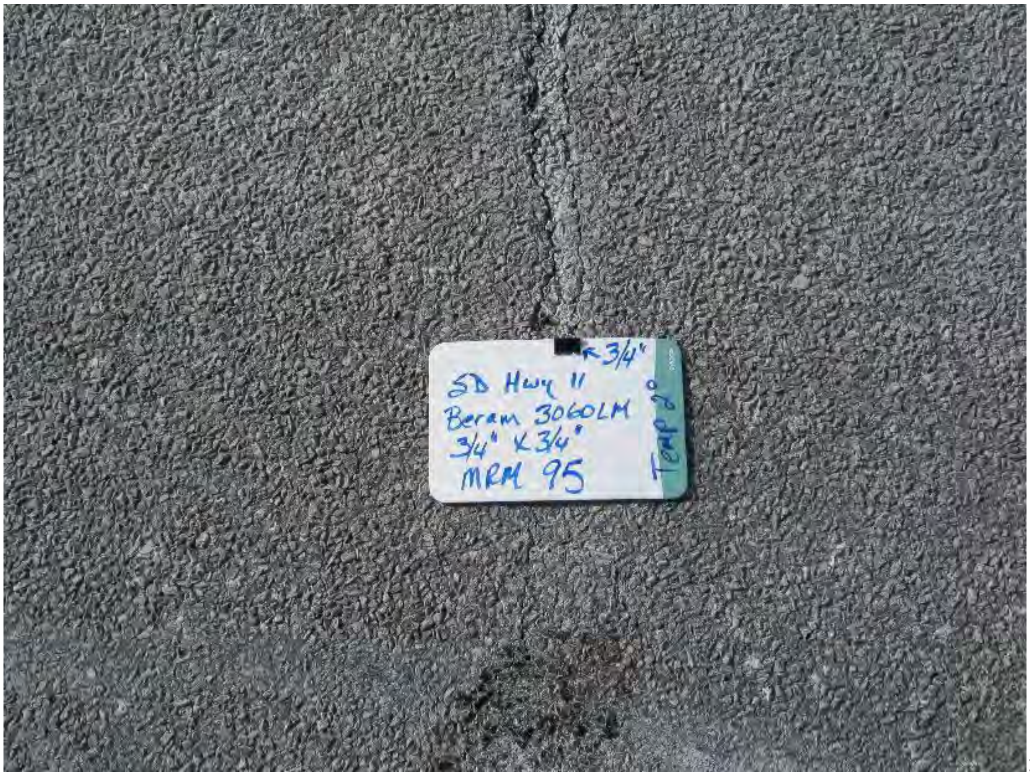


Figure C - 6: Highway 11, MRM 96.

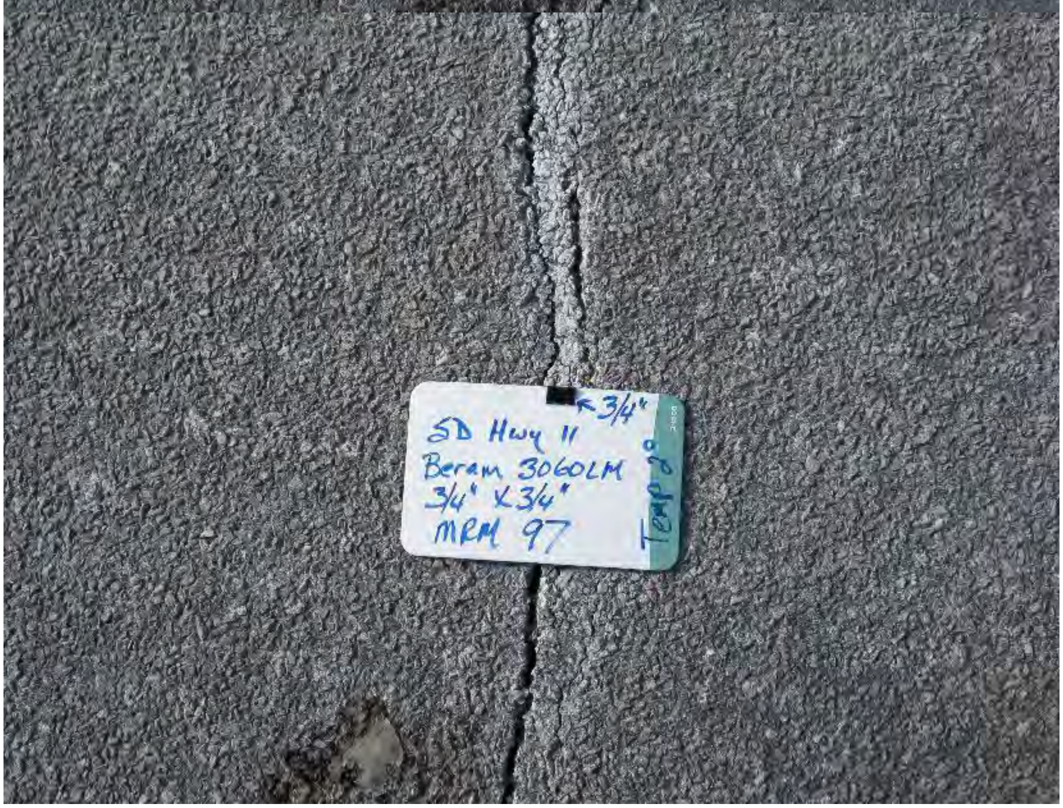


Figure C - 7: Highway 11, MRM 97.

Figure C - 8: Highway 11, MRM 98.

Figure C - 9: Highway 11, MRM 99.

Figure C - 10: Highway 11, MRM 100.

Figure C - 11: Highway 11, MRM 101.

Figure C - 12: Highway 11, MRM 102.

Figure C - 13: Highway 13, MRM 107

Figure C - 14: Highway 13, MRM 109.

Figure C - 15: Highway 13, MRM 110.

Figure C - 16: Highway 13, MRM 112.

Figure C - 17: Highway 17, MRM 44.

Figure C - 18: Highway 17, MRM 45

Figure C - 19: Highway 17, MRM 46.

Figure C - 20: Highway 17, MRM 47.

Figure C - 21: Highway 17, MRM 49.

Figure C - 22: Highway 17, MRM 50.

Figure C - 23: Highway 17, MRM 51.

Figure C - 24: Highway 17, MRM 52.

Figure C - 25: Highway 38, MRM 349.

Figure C - 26: Highway 38, MRM 350.

Figure C - 27: Highway 38, MRM 351.

Figure C - 28: Highway 38, MRM 353.

Figure C - 29: Highway 38, MRM 354.

Figure C - 30: Highway 38, MRM 355.


SD Hwy 38
Deery 1D1ELT
3/4" X 3/4"
MRM 356

Figure C - 31: Highway 38, MRM 356.

Figure C - 32: Highway 38, MRM 357.

Figure C - 33: Highway 38, MRM 358.

Figure C - 34: Highway 38, MRM 359.


SD Hwy 38
Deery 101ELT
3/4" X 3/4"
mRm 361


SD Hwy 38
Deery 101ELT
3/4" X 3/4"
mRm 360

Figure C - 35: Highway 38, MRM 360.

Figure C - 36: Highway 38, MRM 361.

Figure C - 37: Highway 38, MRM 362.

Figure C - 38: Highway 38, MRM 363.


mRm 396


SD Hwy 38
Deery 101ELT
3/4" X 3/4"
mRm 364

Figure C - 39: Highway 38, MRM 364.

Figure C - 40: Highway 44, MRM 396.

Figure C - 41: Highway 44, MRM 397.

Figure C - 42: Highway 44, MRM 398.

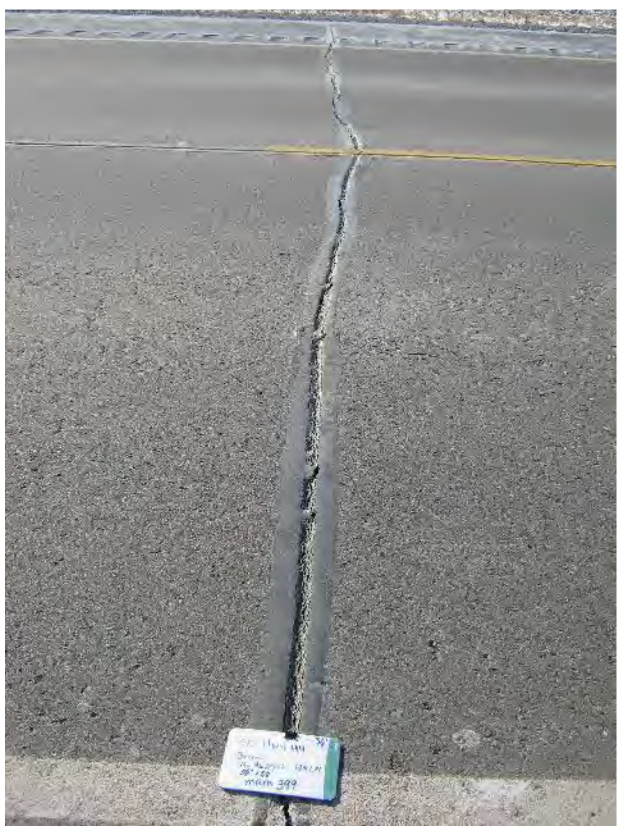


Figure C - 43: Highway 44, MRM 399.

Figure C - 44: Highway 44, MRM 400.

Figure C - 45: Highway 44, MRM 401.

Figure C - 46: Highway 44, MRM 402.


SD Hwy 44
MRM 404

Figure C - 47: Highway 44, MRM 403.

Figure C - 48: Highway 44, MRM 404.

Figure C - 49: Highway 44, MRM 405.

Figure C - 50: Highway 44, MRM 406.

Figure C - 51: Highway 81, MRM 95.

Figure C - 52: Highway 81, MRM 96.

Figure C - 53: Highway 81, MRM 98.

Figure C - 54: Highway 81, MRM 99.

Figure C - 55: Highway 81, MRM 100.

Figure C - 56: Highway 81, MRM 101.

Figure C - 57: Highway 81, MRM 102.

Figure C - 58: Highway 81, MRM 103.

Figure C - 59: Highway 81, MRM 104.

Figure C - 60: Highway 81, MRM 105.


107


106

Figure C - 61: Highway 81, MRM 106.

Figure C - 62: Highway 81, MRM 107.

APPENDIX D CRACK SEALANT INSTALLATION DATA SHEET

General Information

Name: Date:

Location Information

Highway No.:

Milepost location: _____________ to _____________

Direction (circle all that apply): Eastbound Westbound Northbound Southbound

Pavement Information

Most recent road improvement (circle one): None Chip seal Overlay New pavement

Date of most recent improvement:

Pavement condition (circle one): Poor Fair Good Very Good Excellent

Approx. distance between adjacent cracks (ft.):

Pavement temperature (°F):

Crack Sealing Information

Date of installation:

Name of installer/contractor:

Sealant name/manufacturer:

Was a sample of the sealant taken for testing (circle one)? Yes No Don't know

Ambient conditions during installation: Temp. (°F): _______ Rel. humidity (%): _______

Avg. crack width prior to routing (in.):

Method of cleaning crack (circle all that apply): compressed air hot air lance (______°F)

Presence of water in/near crack (circle one): 1 2 3 4 5 (1 = dry, 3 = moist, 5 = wet)

Rout configuration: Width (in.): _______ Depth (in.): _______ □ Not routed

□ Overband used	□ Blotter material used	Kettle temp. (°F): ________

Notes:

APPENDIX E WINTER - WINTER - SUMMER SEALANT INSPECTION COMPARISON

Highmore, Mod 4 3405 (Right Pointe)

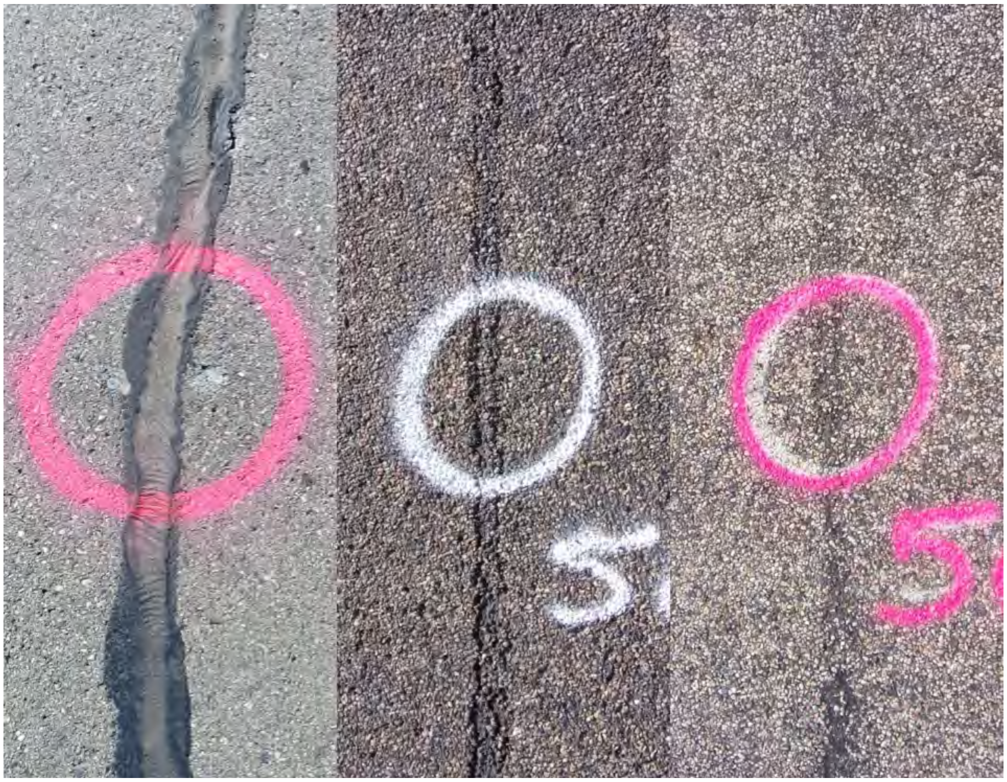
2/10/2018	3/21/19	8/18/2019

Highmore, Elastoflex 72

2/10/2018	3/21/19	8/18/2019

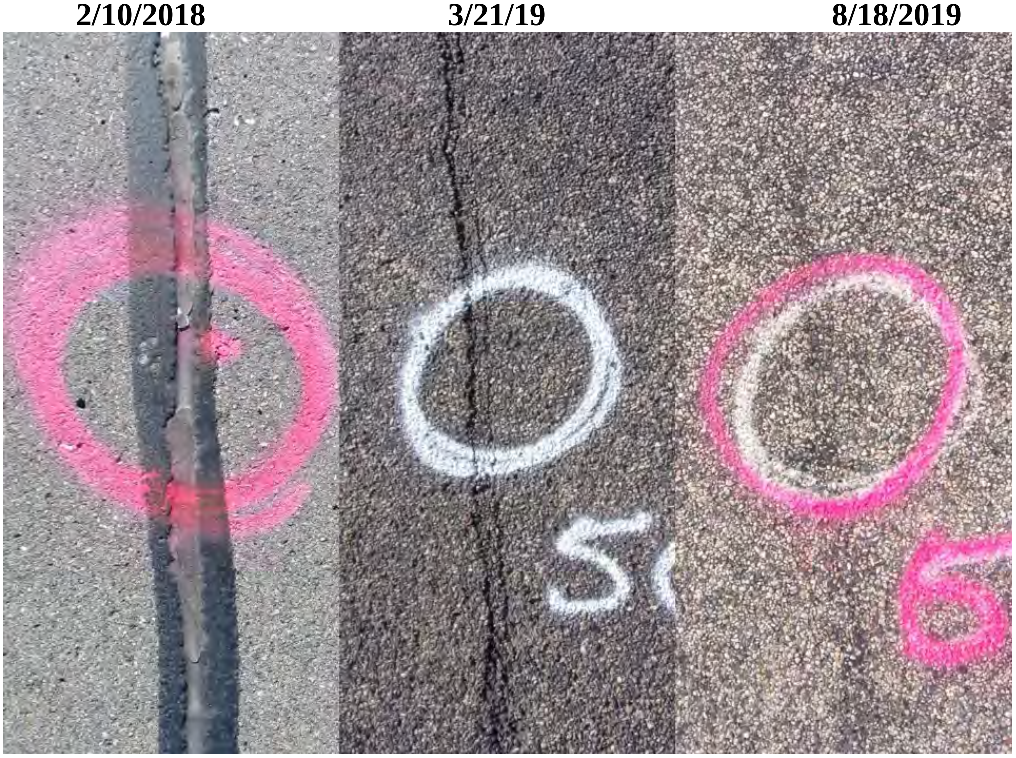
Highmore, Crafco Roadsaver 522

2/10/2018	3/21/19	8/18/2019



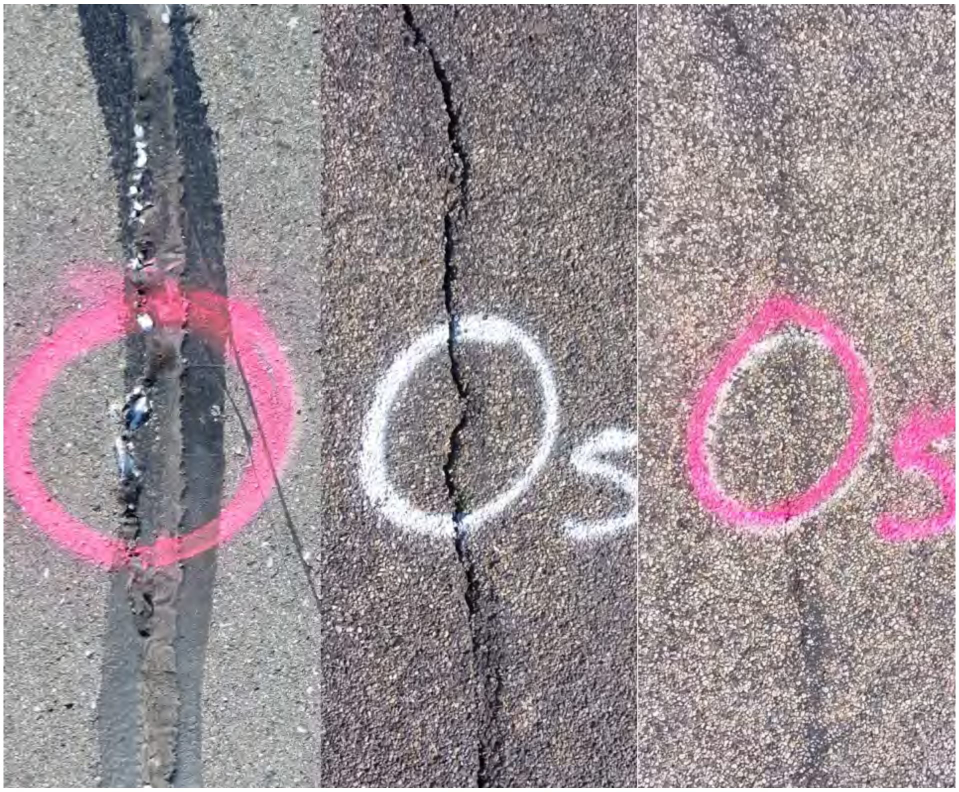
Highmore, 3405 M (W.R. Meadows)

2/10/2018	3/21/19	8/18/2019



Highmore, Deery 101 SD

2/10/2018 **3/21/19** **8/18/2019**



Highmore, Crafco Roadsaver 231 SD

2/10/2018 **3/21/19** **8/18/2019**

Highmore, Deery 101 ELT

2/10/2018 **3/21/19** **8/18/2019**

Highmore, McAsphalt 6690

2/10/2018 **3/21/19** **8/18/2019**

Yankton, Mod 4 3405 (Right Pointe)

2/11/2018 **3/22/19** **8/17/2019**

Yankton, Elastoflex 72

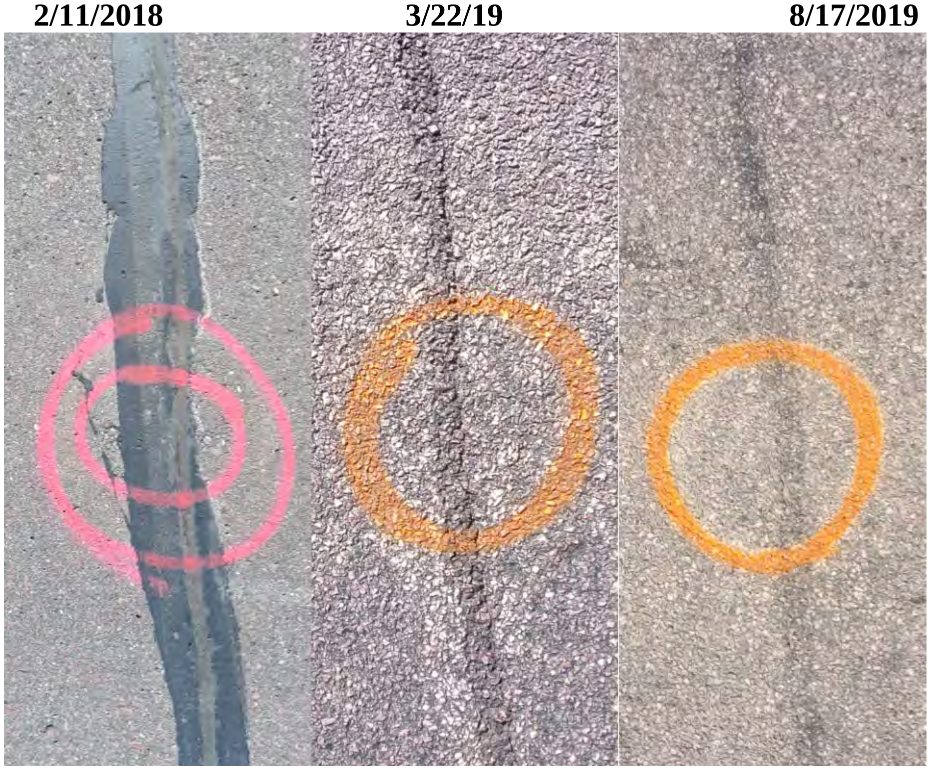
2/11/2018 **3/22/19** **8/17/2019**

Yankton, Crafco Roadsaver 522

2/11/2018 **3/22/19** **8/17/2019**

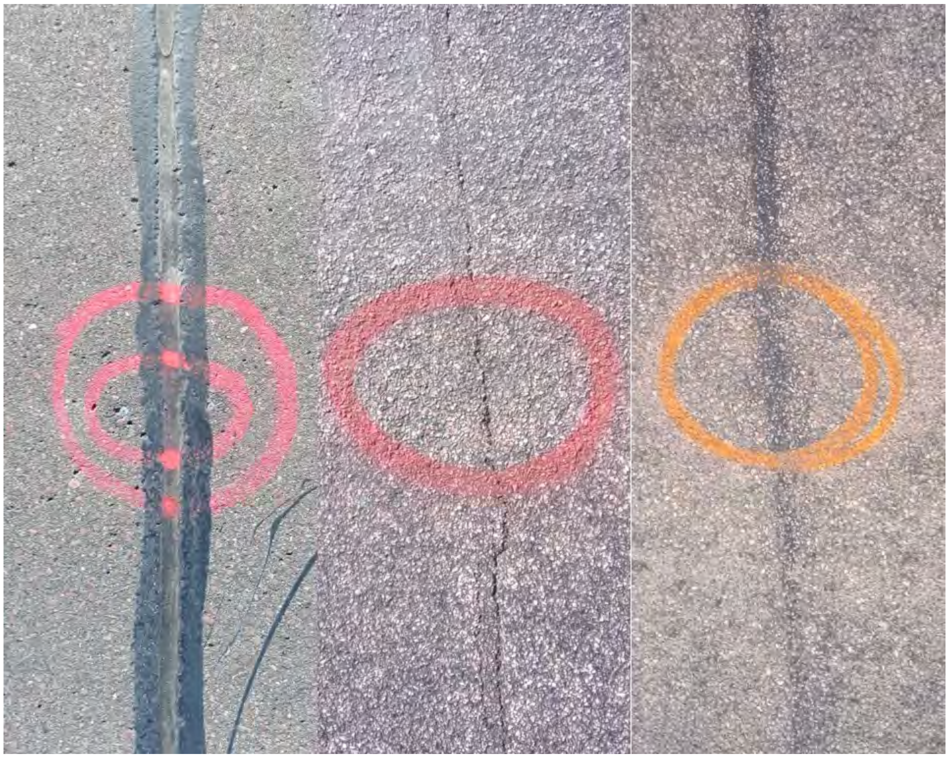
Yankton, 3405 M (W.R. Meadows)

2/11/2018 **3/22/19** **8/17/2019**



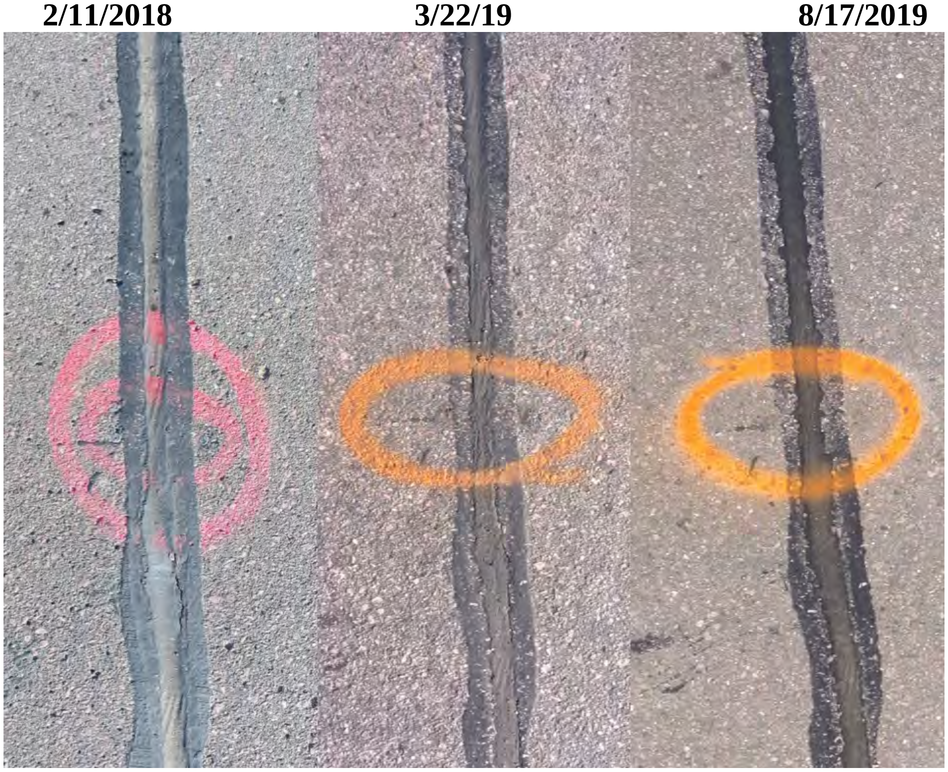
Yankton, Deery 101 SD

2/11/2018 **3/22/19** **8/17/2019**



Yankton, Crafco Roadsaver 231 SD

2/11/2018 **3/22/19** **8/17/2019**

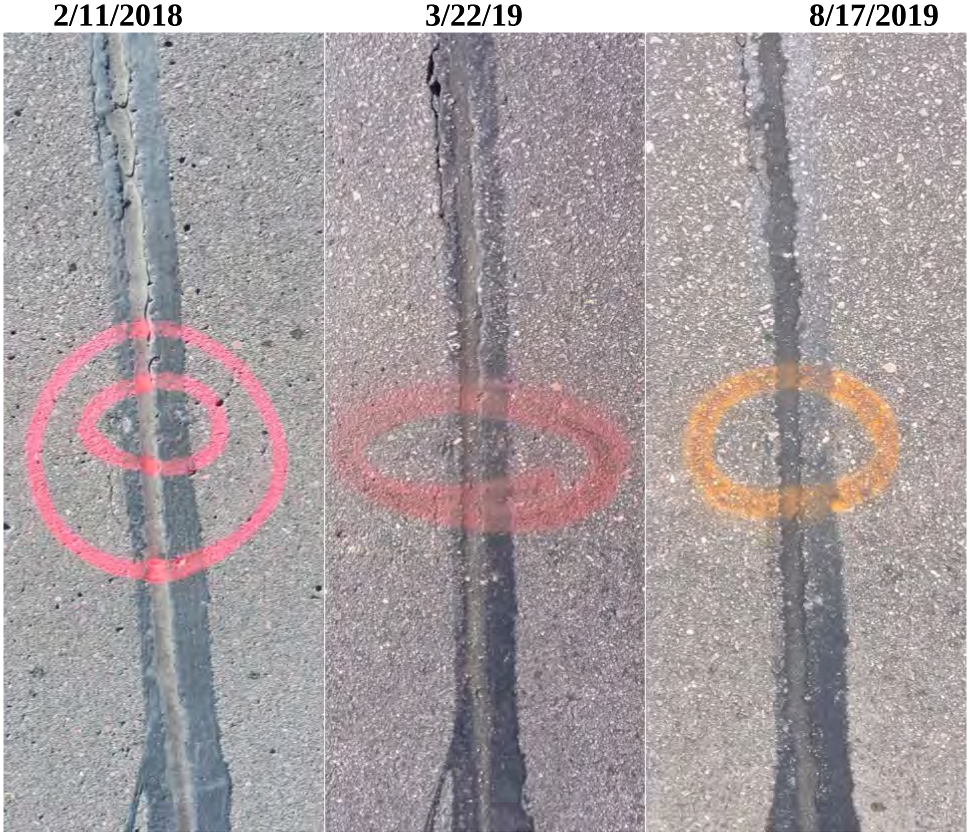


Yankton, Deery 101 ELT

2/11/2018 **3/22/19** **8/17/2019**

Yankton, McAsphalt 6690

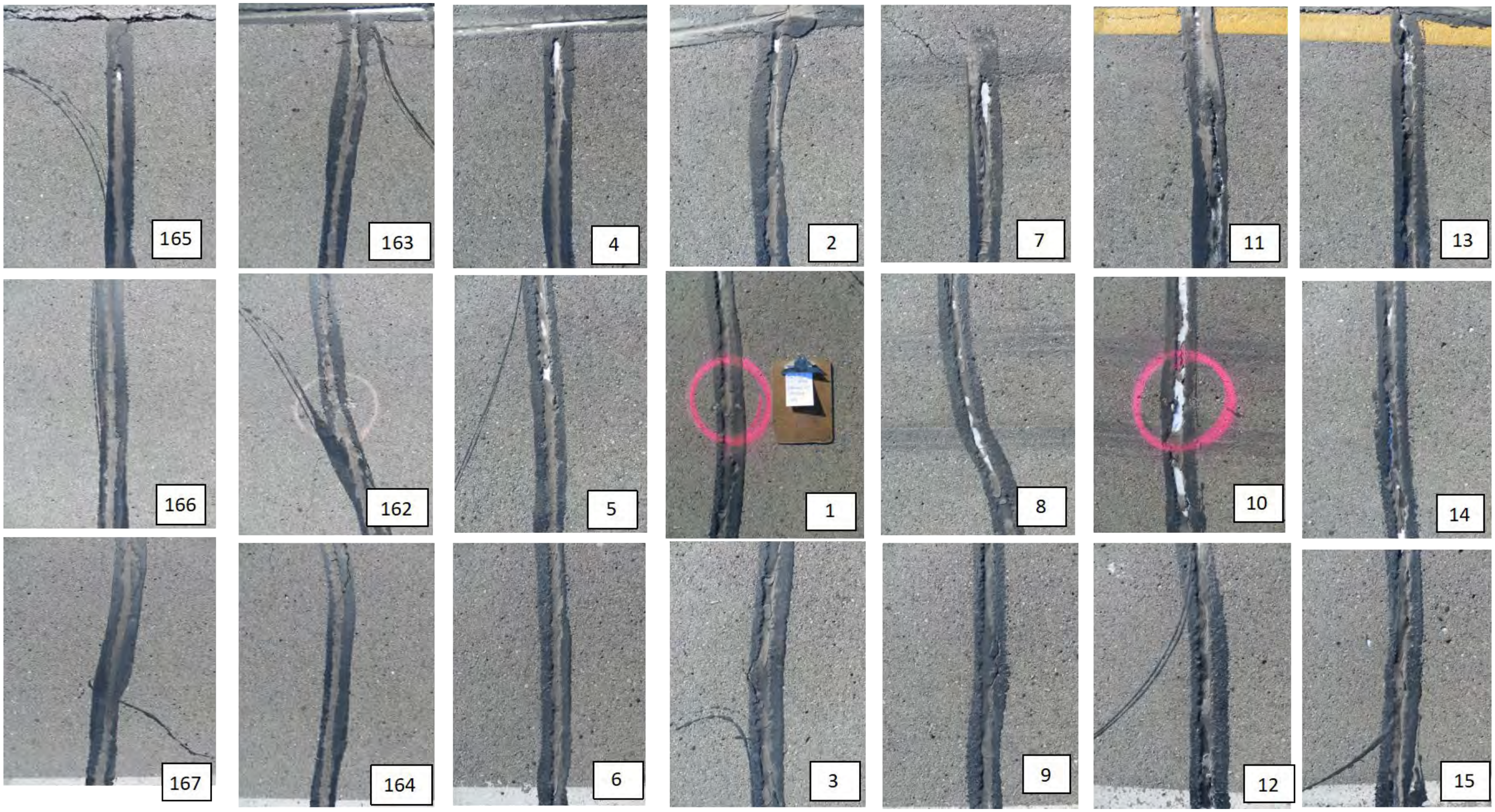
2/11/2018 **3/22/19** **8/17/2019**



APPENDIX F CRACK SEALANT PHOTOGRAPHS; FIRST WINTER INSPECTION

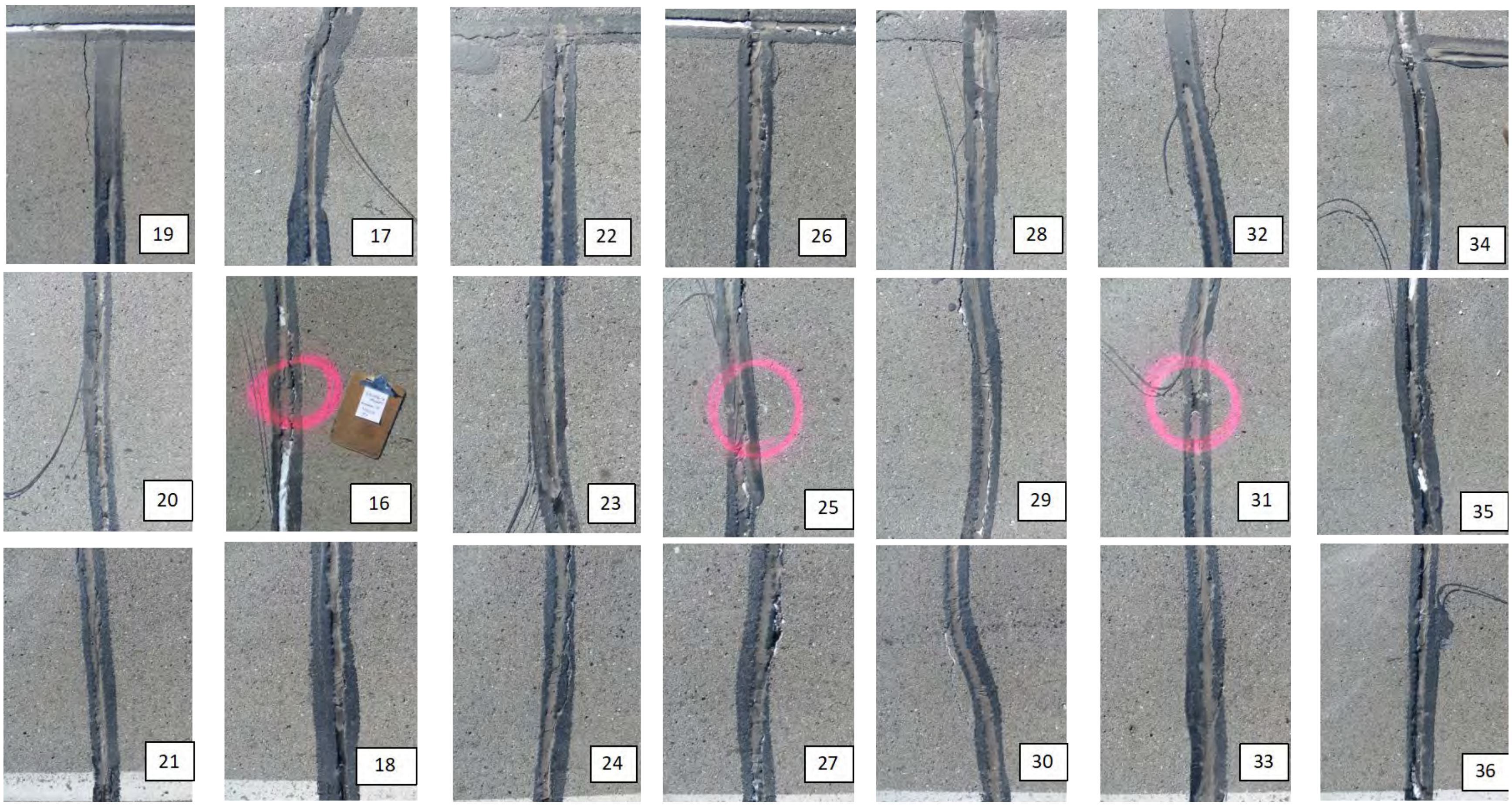
Mod 4 3405 (Right Pointe), Highmore Site, Inspection 1

			Installation 9/6/2017, 9:00am			Inspection 1 2/10/2018, 9:30am	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
1693	58	29	42	61	380	-10F	-12F
1712	✓with MRM values						



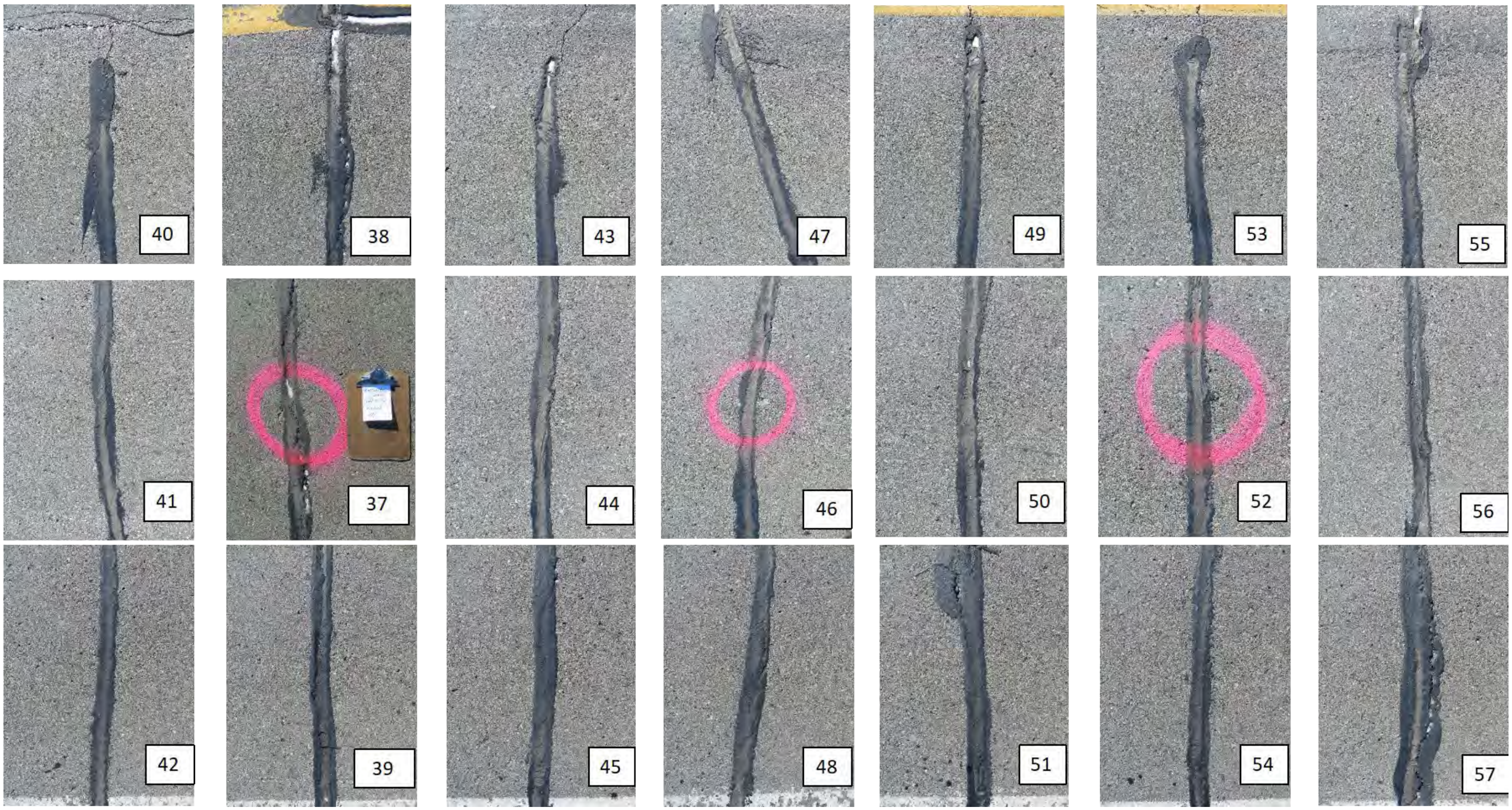
Elastoflex 72 (Maxwell), Highmore Site, Inspection 1

			Installation 9/6/2017, 10:00am			Inspection 1 2/10/2018, 10:00am	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
1595	66	24	55	71	350	-9	-15
1589	✓with MRM values						



Road Saver 522 (Crafco), Highmore Site, Inspection 1

			Installation 9/6/2017, 11:00am			Inspection 1 2/10/2018, 10:30am	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
1890	61	31	65	85	390	-8	0
1889	✓with MRM values						

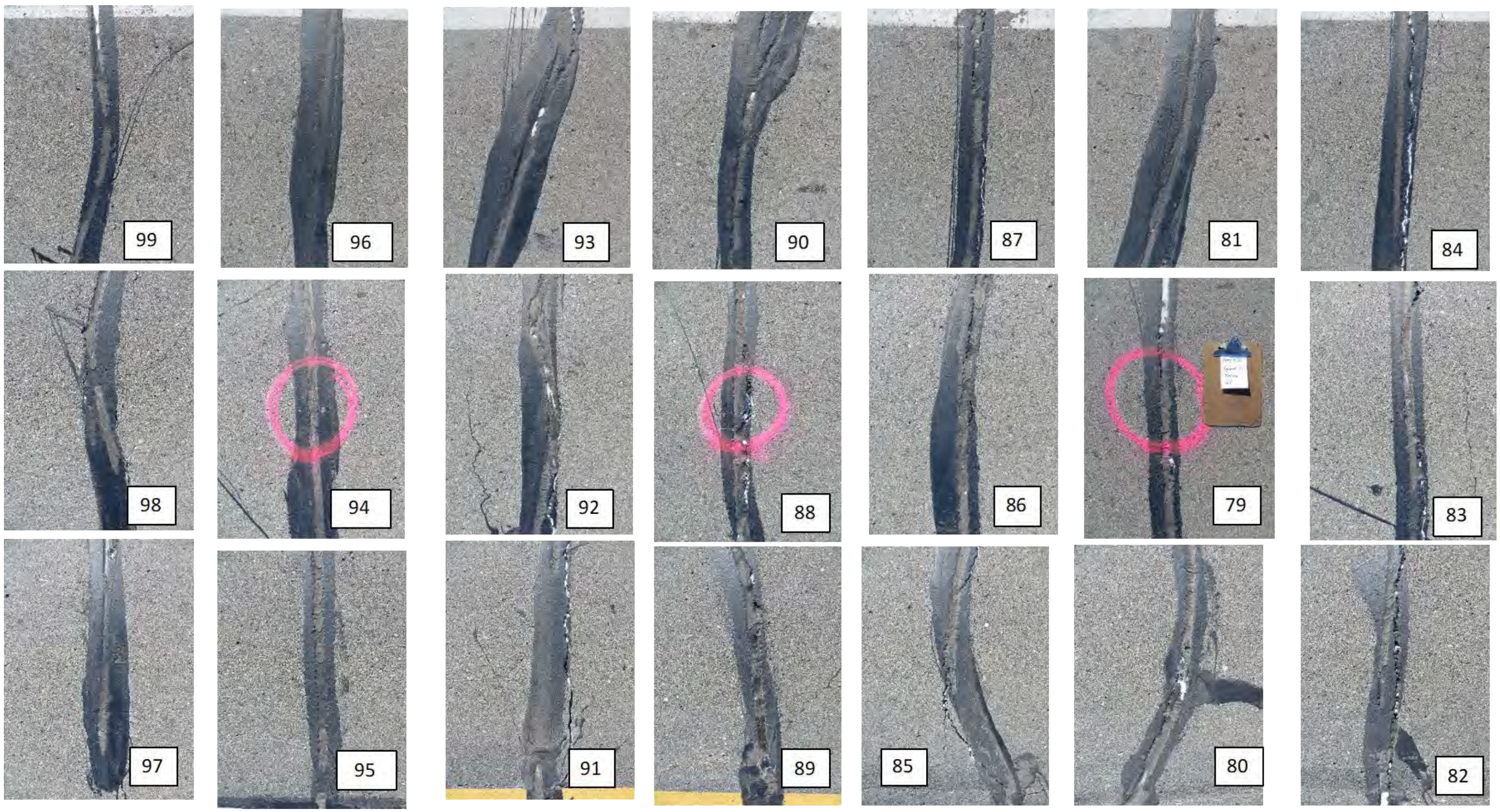


3405 M (WR Meadows), Highmore Site, Inspection 1

			Installation 9/6/2017, 12:00pm			Inspection 1 2/10/2018, 11:00am	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
2108	72	29	66	94	385	-8	0.6
2232	✓with MRM values						

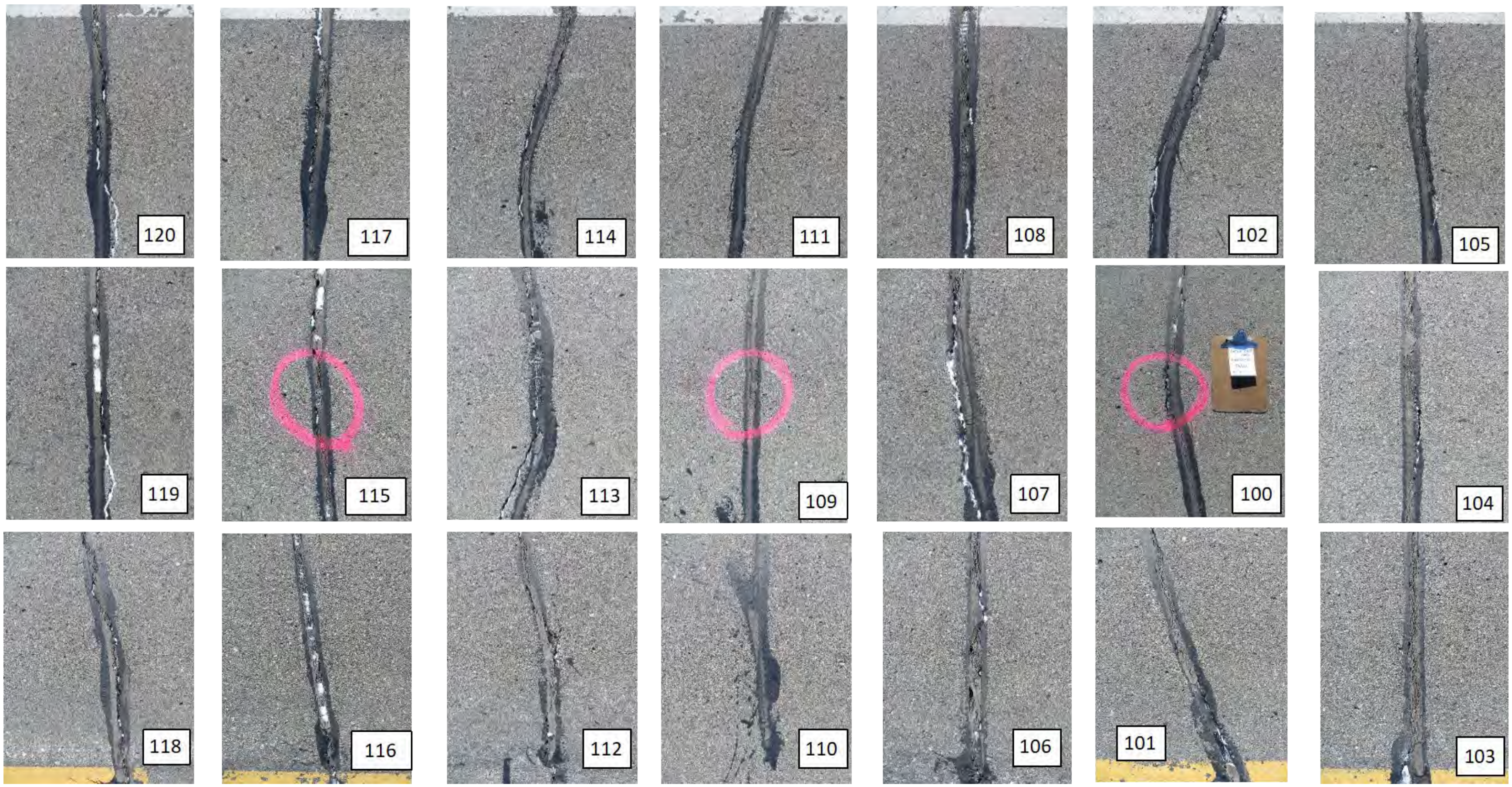
101SD (Deery), Highmore Site, Inspection 1

Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Installation 9/6/2017, 2:00pm Air Temp	Installation 9/6/2017, 2:00pm Pavement Temp	Installation 9/6/2017, 2:00pm Kettle Temp	Inspection 1 2/10/2018, 11:20am Air Temp	Inspection 1 2/10/2018, 11:20am Pavement Temp
2176	63	35	68	112	370	-8	4
2312	✓with MRM values						



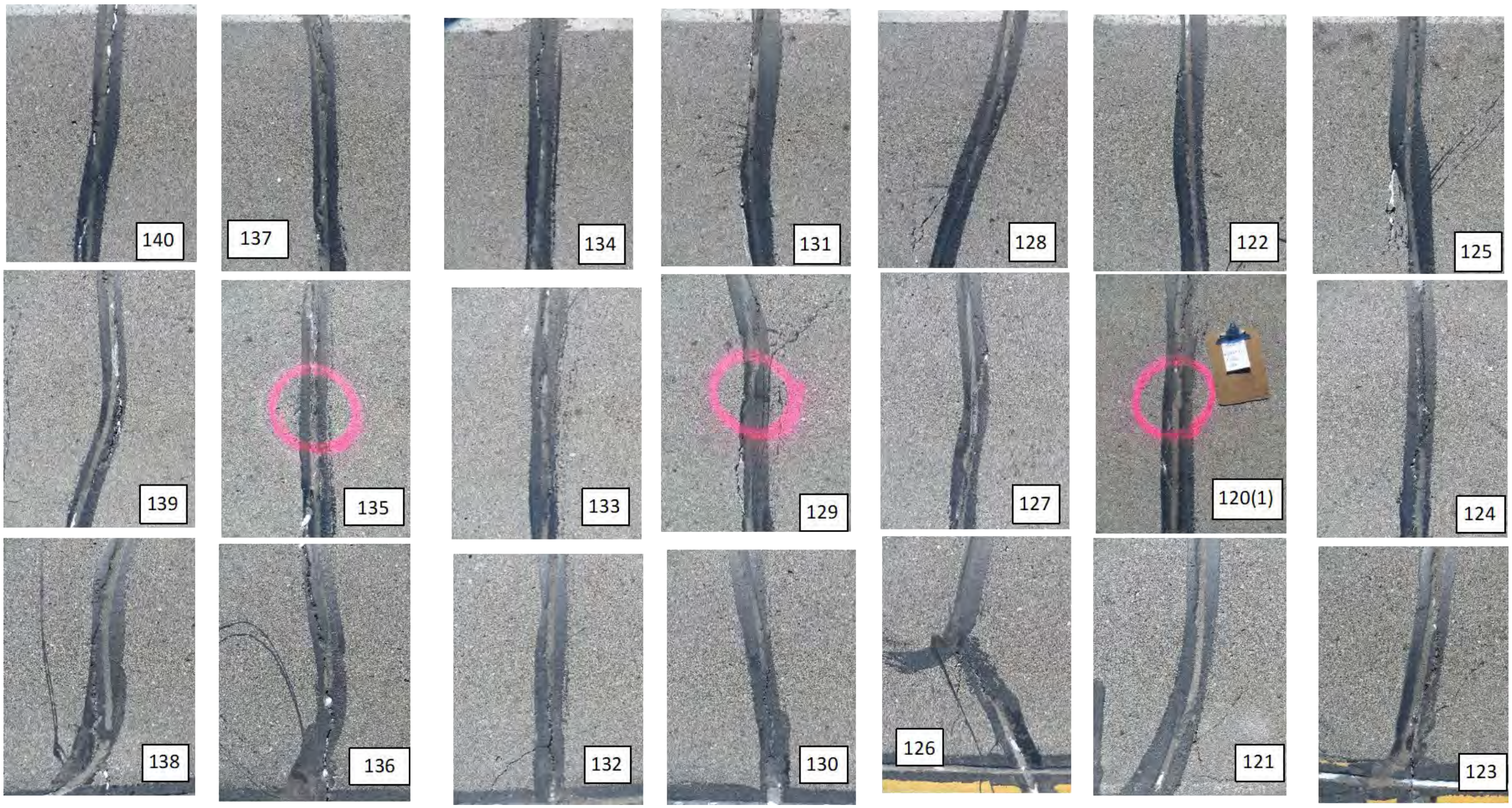
Road Saver 231SD (Crafco), Highmore Site, Inspection 1

			Installation 9/6/2017, 2:30pm			Inspection 1 2/10/2018, 11:45am	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
2246	59	38	68	119	380	-5	10
2237	✓with MRM values						



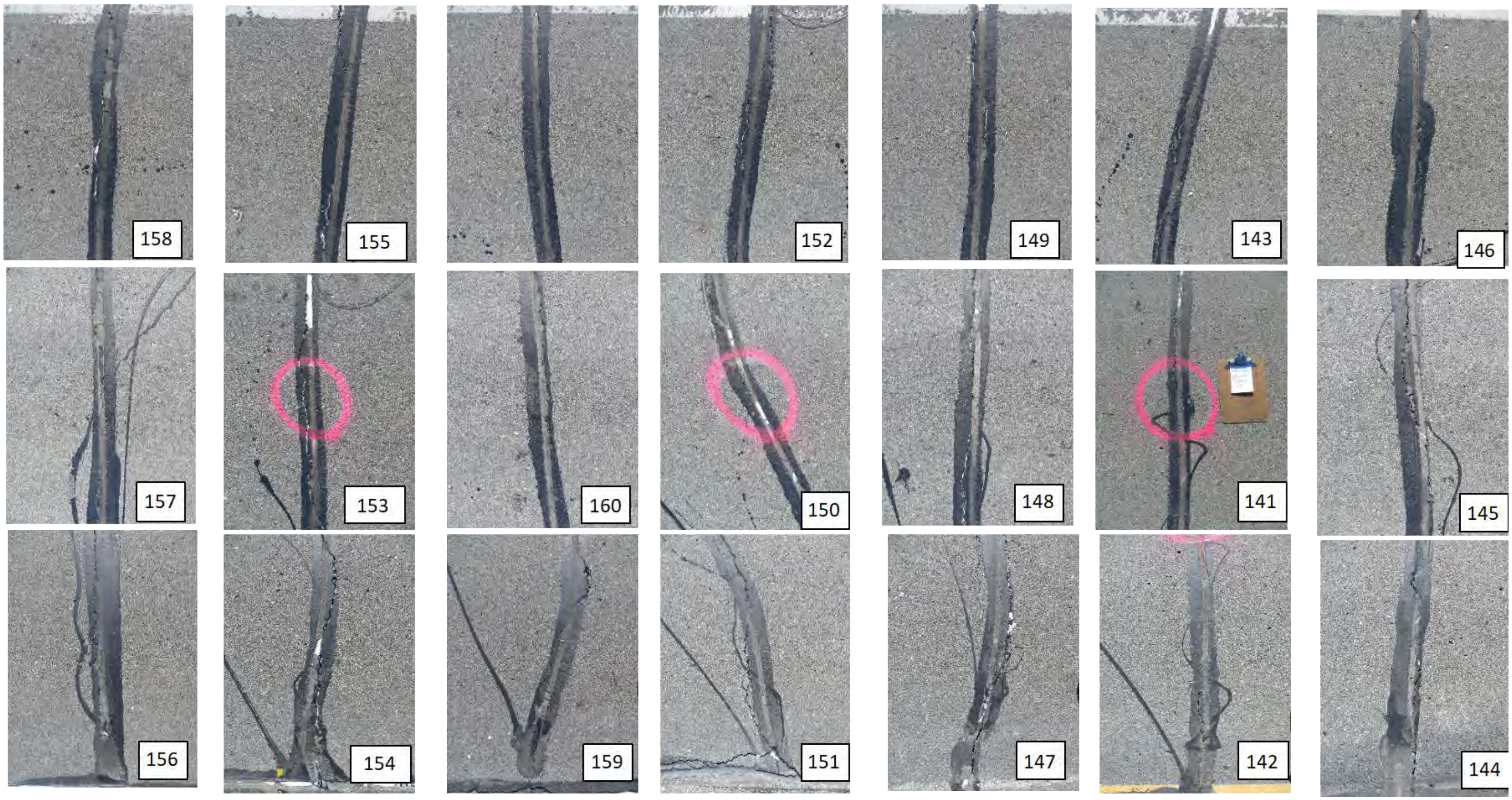
101 ELT (Deery), Highmore Site, Inspection 1

Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Installation 9/6/2017 Air Temp	Installation 9/6/2017 Pavement Temp	Installation 9/6/2017 Kettle Temp	Inspection 1 2/10/2018, 12:10pm Air Temp	Inspection 1 2/10/2018, 12:10pm Pavement Temp
2016	70	29	65	111	370	-5	13
2011	✓with MRM values						



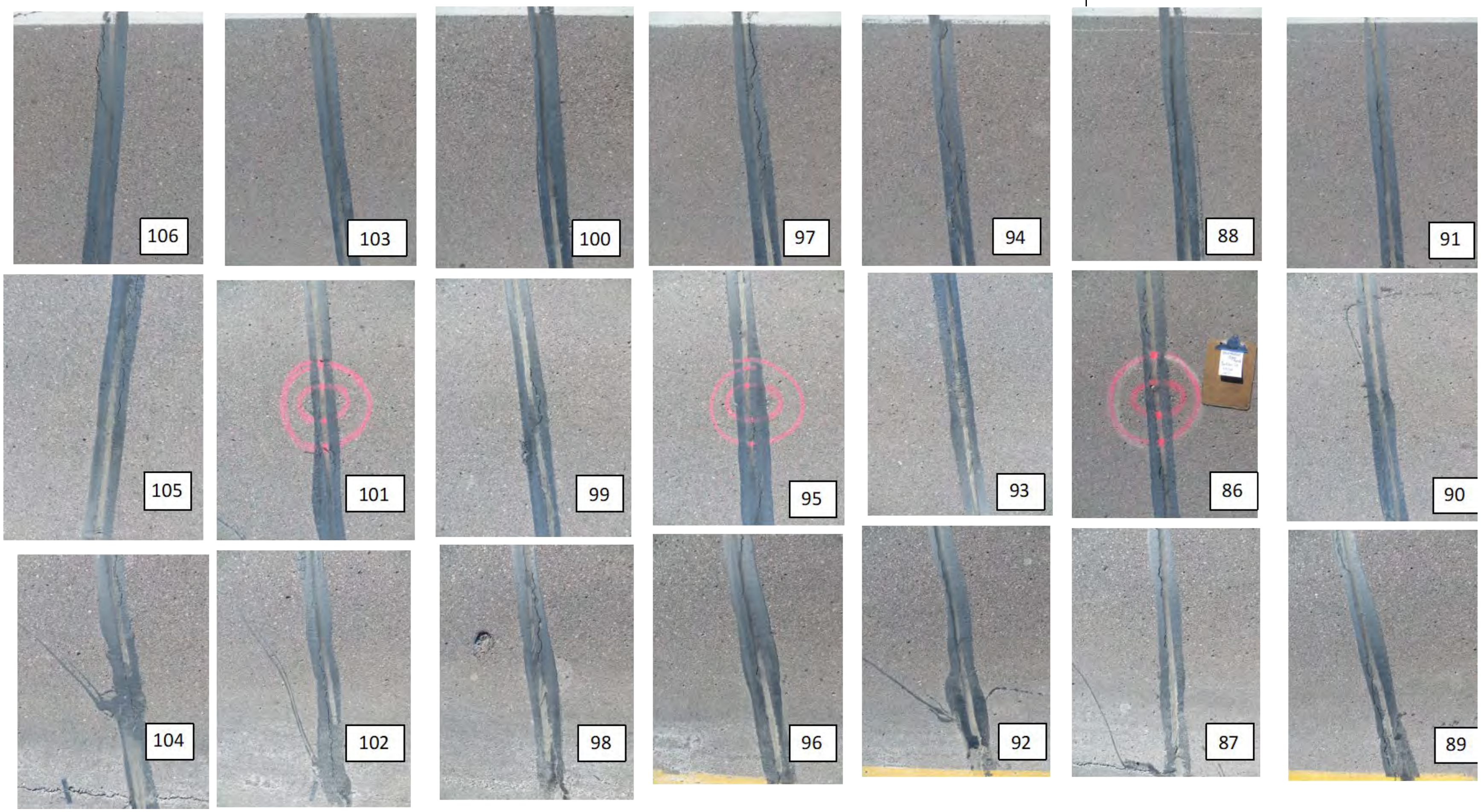
McAsphalt 6690 (Macseal), Highmore Site, Inspection 1

			Installation 9/6/2017, 4:30pm			Inspection 1 2/10/2018, 9:30am	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
1550	58	27	60	115	365	-5	16
1561	✓with MRM values						



Mod 4 3405 (Right Pointe), Yankton Site, Inspection 1

			Installation 9/7/2017, 3:00pm			Inspection 1 2/11/2018, 10:45am	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
2144	62	35	73	114	350	7F	-8F

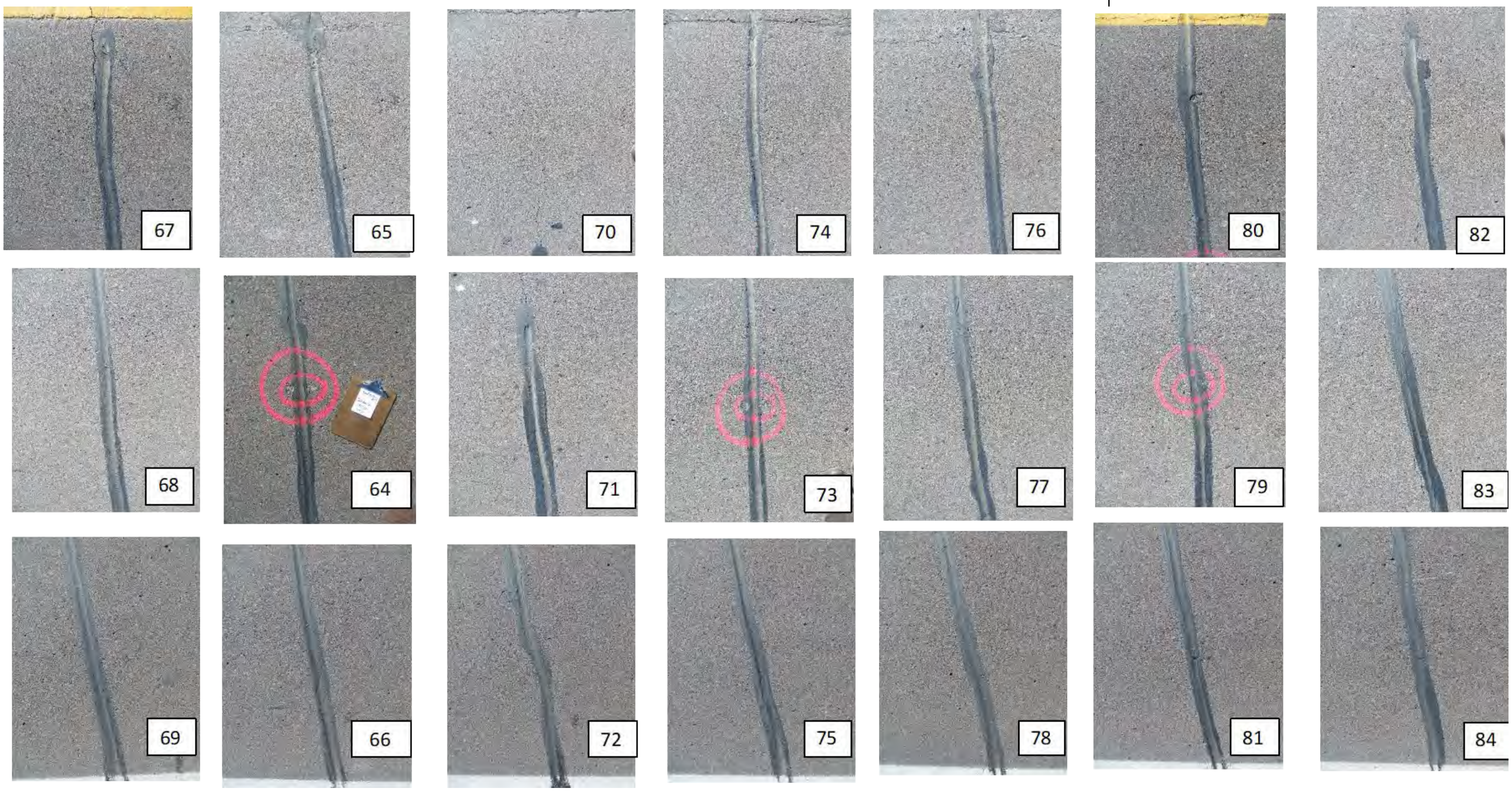


Elastoflex 72 (Maxwell), Yankton Site, Inspection 1

			Installation 9/7/2017			Inspection 1 2/11/2018	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp

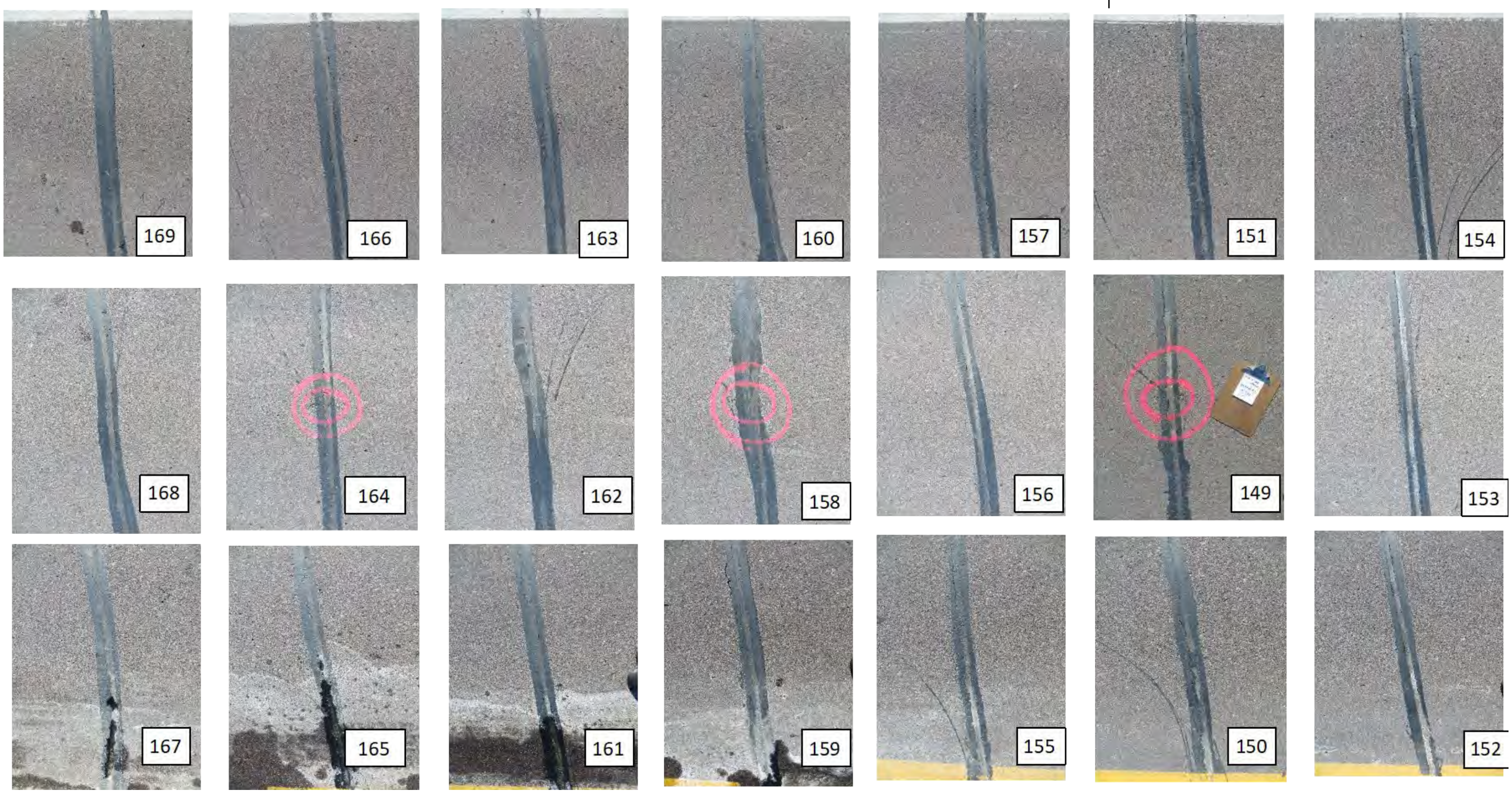
Road Saver 522 (Crafco), Yankton Site, Inspection 1

			Installation 9/7/2017, 11:00am			Inspection 1 2/11/2018, 10:15am	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
1595	87	18	69	87	365	7F	-9F



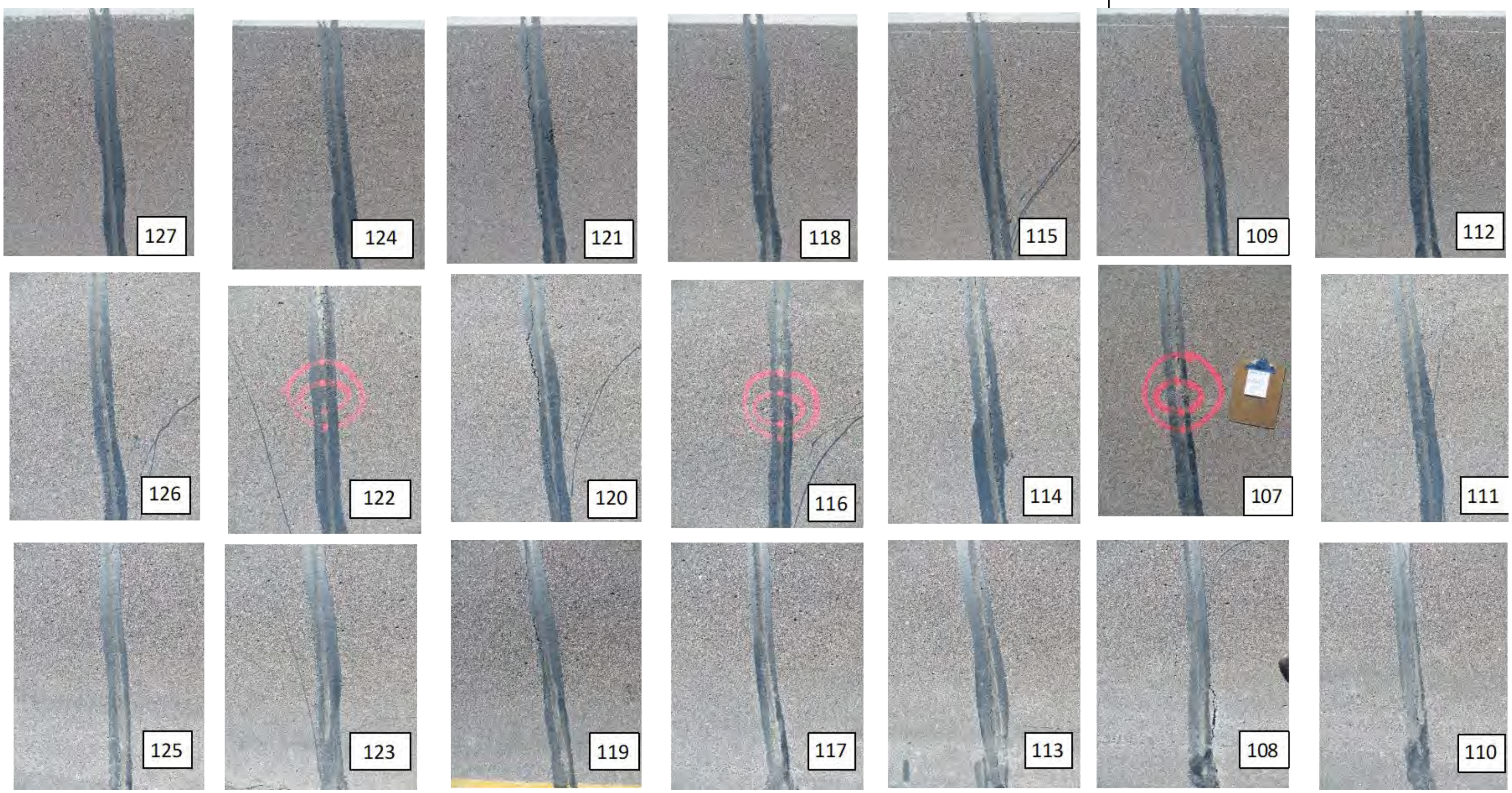
3405 M (WR Meadows), Yankton Site, Inspection 1

			Installation 9/7/2017			Inspection 1 2/11/18	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp



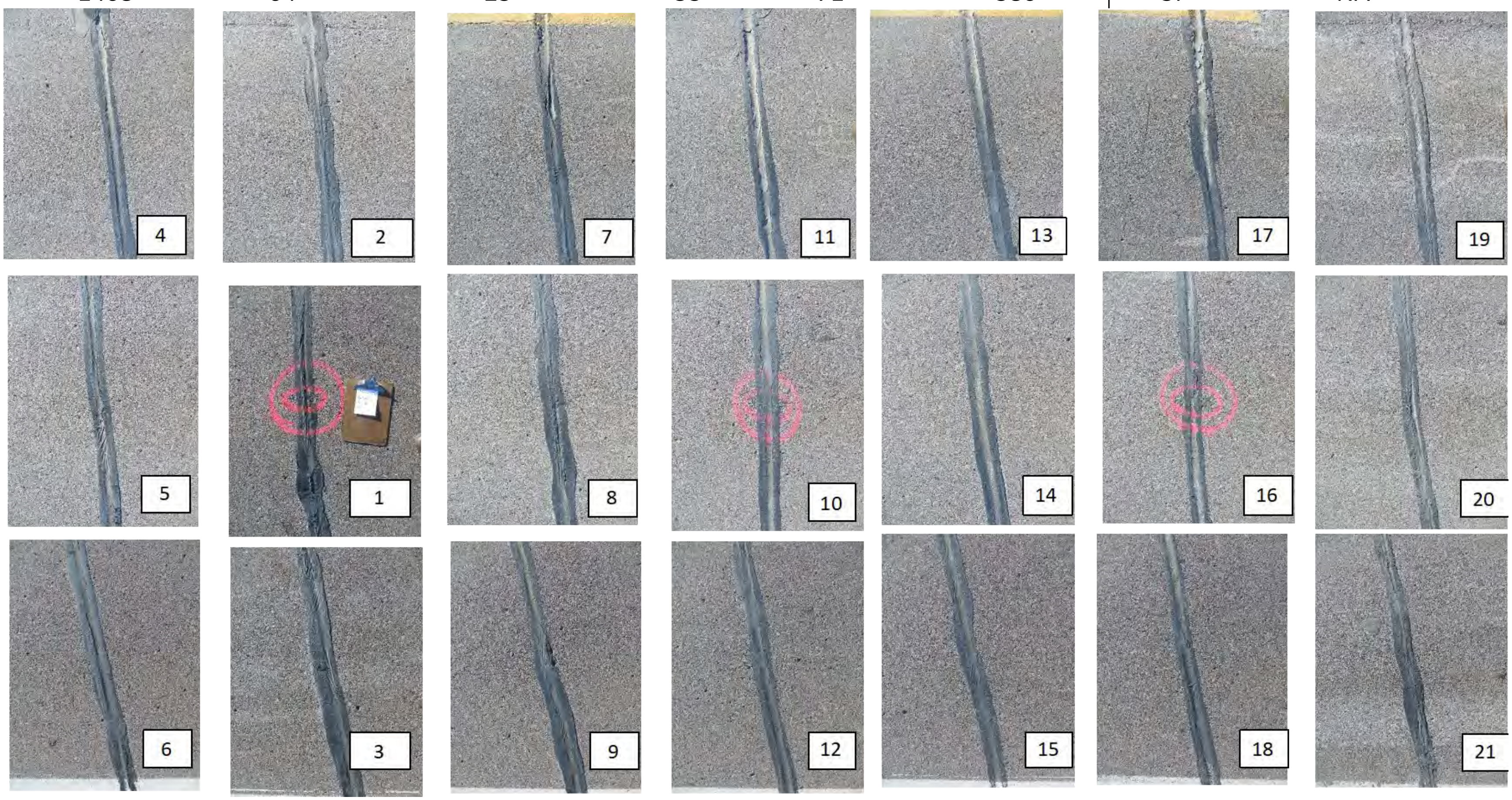
101SD (Deery), Yankton Site, Inspection 1

			Installation 9/7/2017			Inspection 1 2/11/18	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp



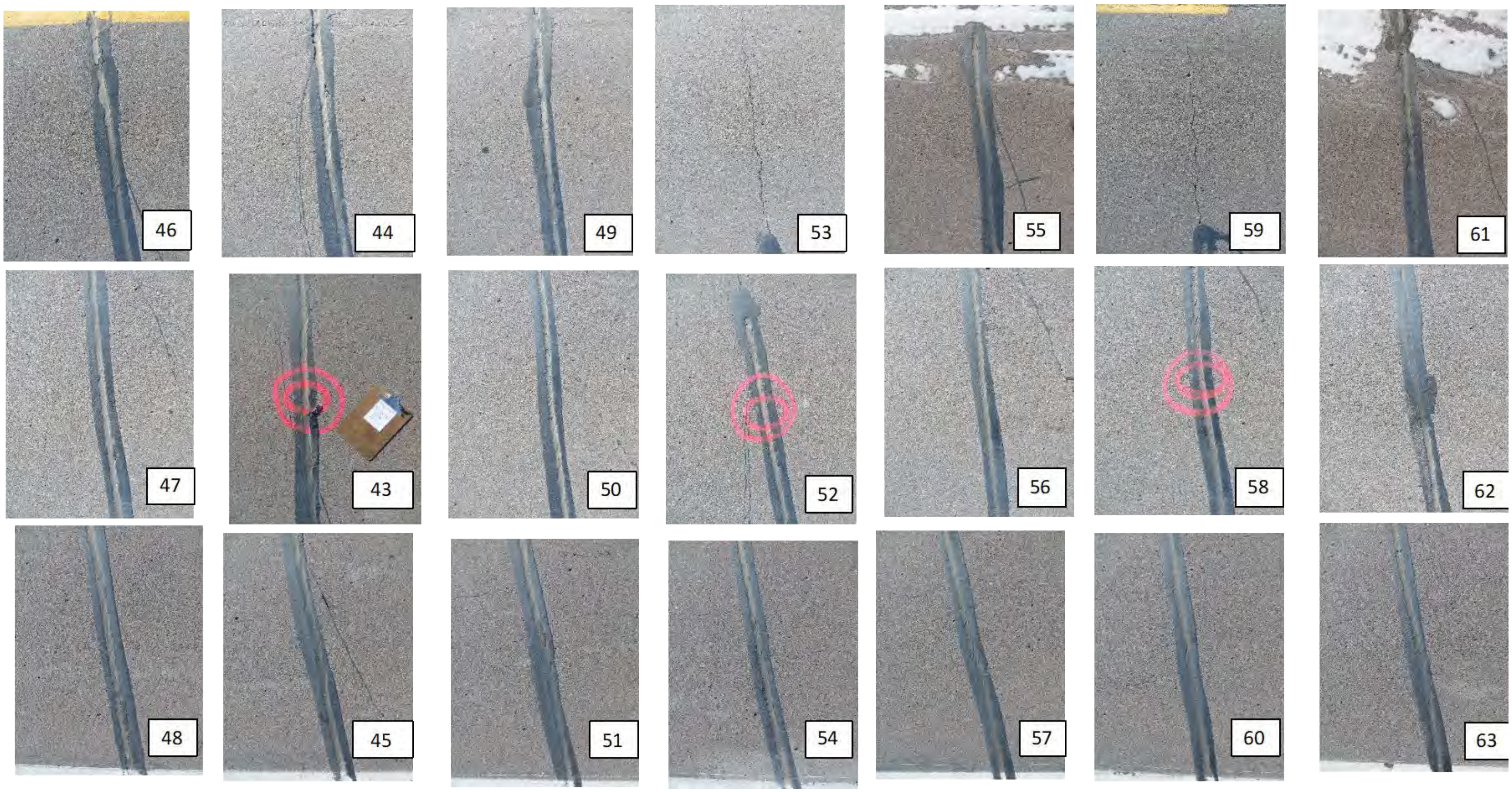
Road Saver 231SD (Crafco), Yankton Site, Inspection 1

Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Installation 9/7/2017, 9:15am			Inspection 1 2/11/2018, 9:00am	
			Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
1468	64	23	53	71	380	5F	NA



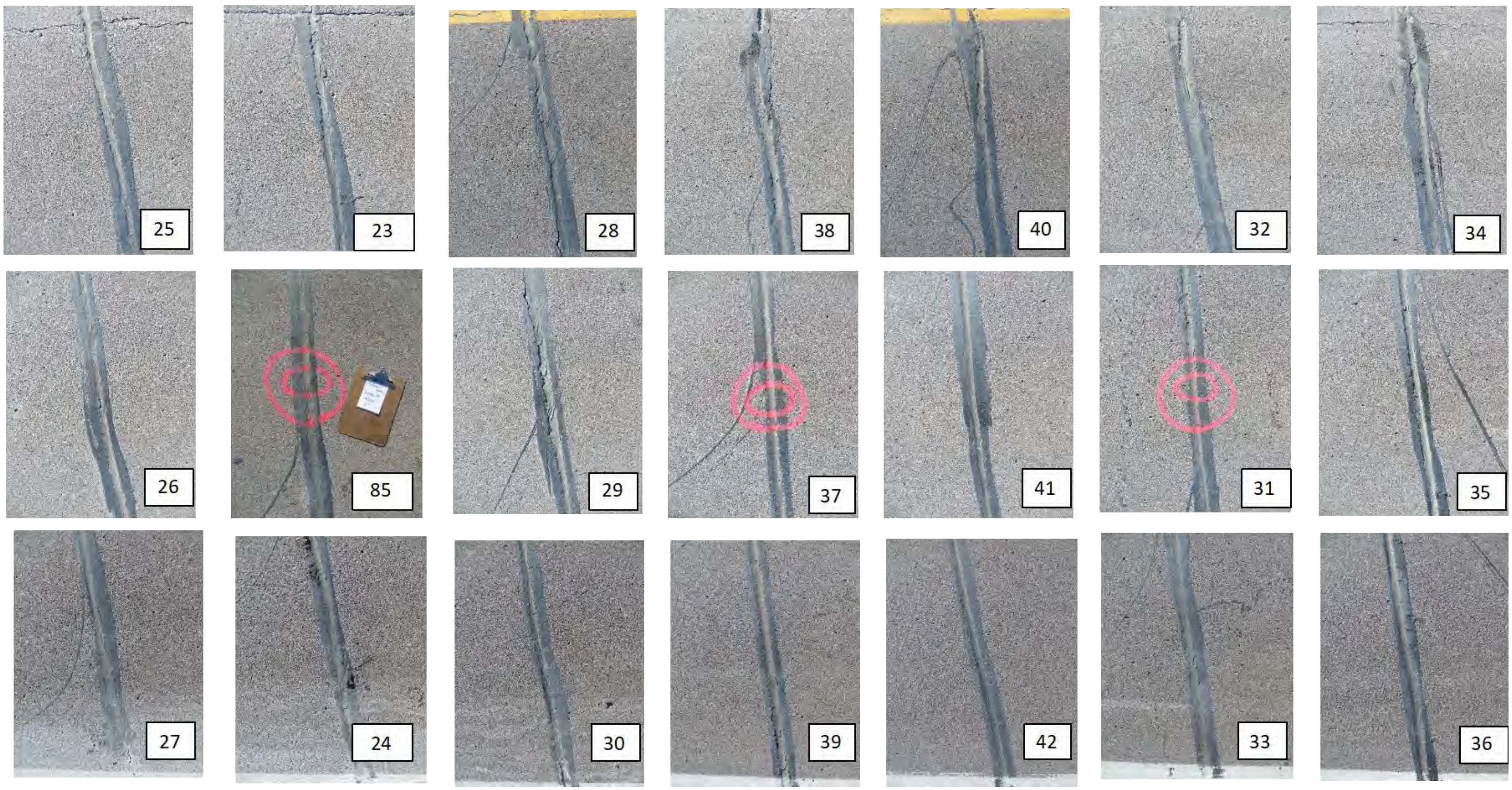
101 ELT (Deery), Yankton Site, Inspection 1

			Installation 9/7/2017, 10:30am			Inspection 1 2/11/2018, 10:00am	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
1309	73	18	59	74	385	6F	-10F



McAsphalt 6690 (Macseal), Yankton Site, Inspection 1

Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Installation 9/7/2017, 9:30am Air Temp	Installation 9/7/2017, 9:30am Pavement Temp	Installation 9/7/2017, 9:30am Kettle Temp	Inspection 1 2/11/2018, 9:30am Air Temp	Inspection 1 2/11/2018, 9:30am Pavement Temp
1346	62	22	55	74	380	6F	-14F



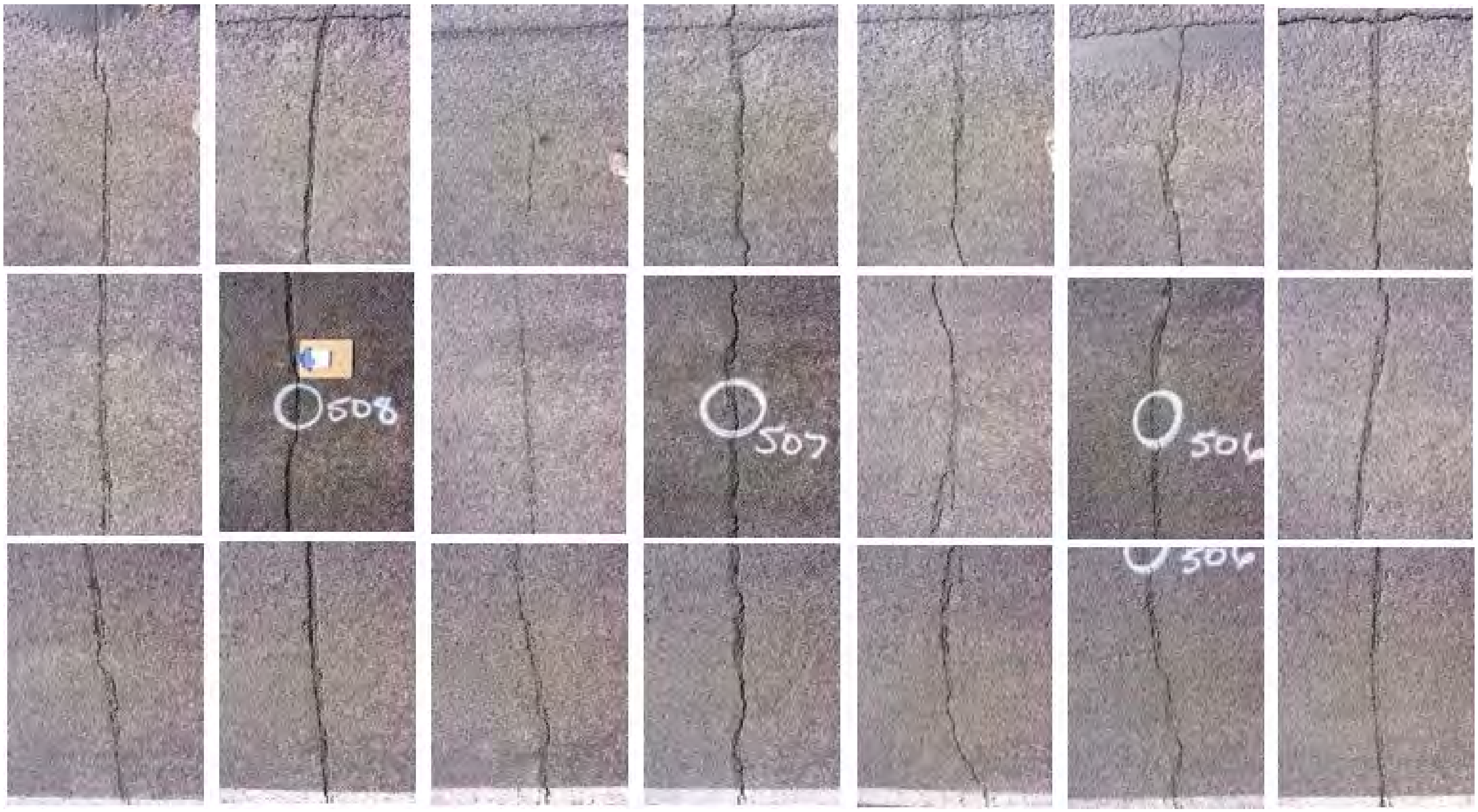
APPENDIX G CRACK SEALANT PHOTOGRAPHS; SECOND WINTER INSPECTION

Mod 4 3405 (Right Pointe), Highmore Site

			Installation 9/6/2017, 9:00am			Inspection 3 3/21/19	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
1693	58	29	42	61	380		
1712	✓with MRM values						

Elastoflex 72 (Maxwell), Highmore Site, Inspection 3

			Installation 9/6/2017, 10:00am			Inspection 3 3/21/19	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
1595	66	24	55	71	350		
1589	✓with MMR values						

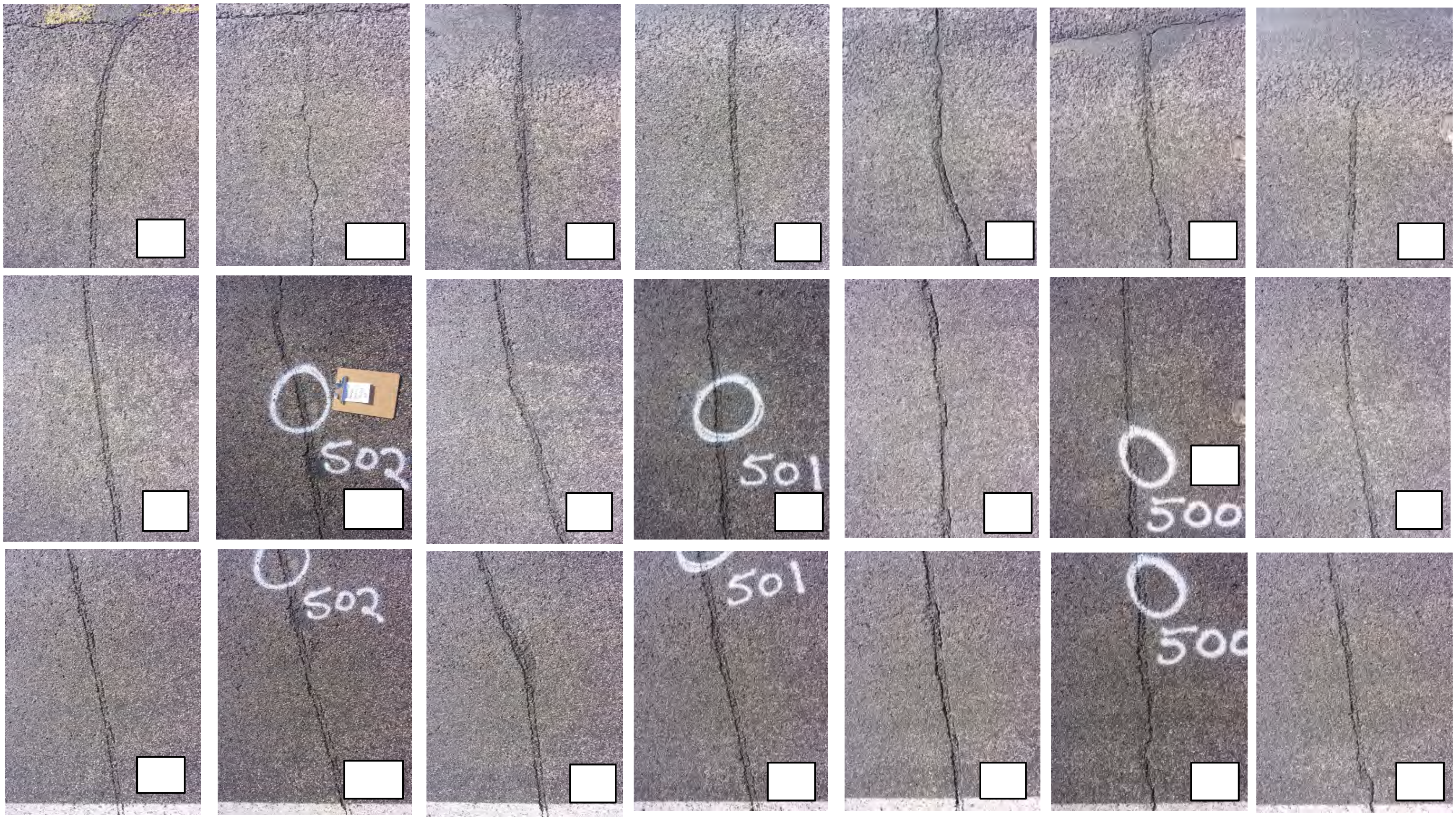


Road Saver 522 (Crafco), Highmore Site, Inspection 3

Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Installation 9/6/2017, 11:00am Air Temp	Installation 9/6/2017, 11:00am Pavement Temp	Installation 9/6/2017, 11:00am Kettle Temp	Inspection 3 3/21/19 Air Temp	Inspection 3 3/21/19 Pavement Temp
1890	61	31	65	85	390		
1889	✓with MMR values						

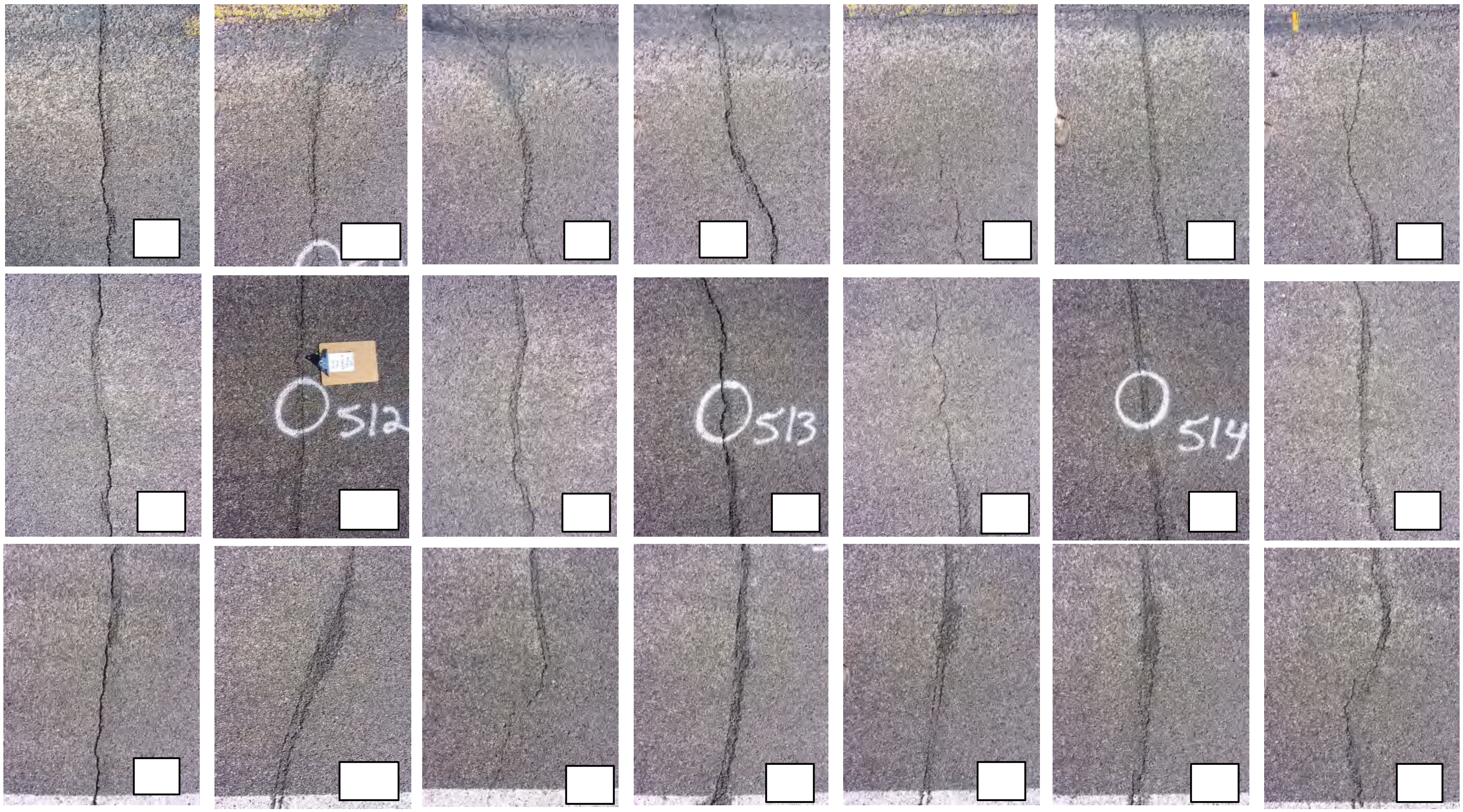
3405 M (WR Meadows), Highmore Site, Inspection 3

			Installation 9/6/2017, 12:00pm			Inspection 3 3/21/19	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
2108	72	29	66	94	385		
2232	✓with MMR values						



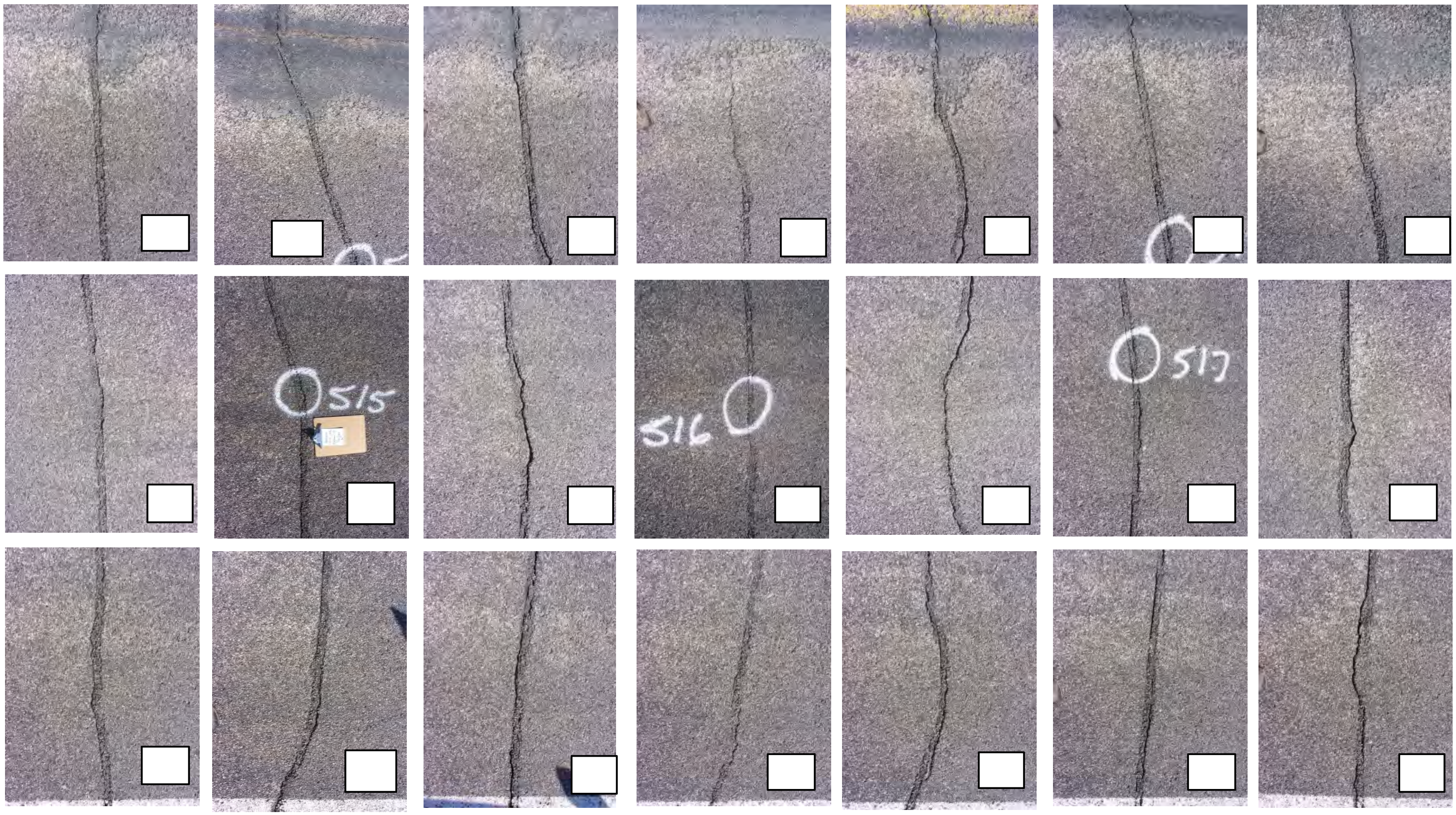
101SD (Deery), Highmore Site, Inspection 3

Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Installation 9/6/2017, 2:00pm			Inspection 3 3/21/19	
			Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
2176	63	35	68	112	370		
2312	✓with MRM values						



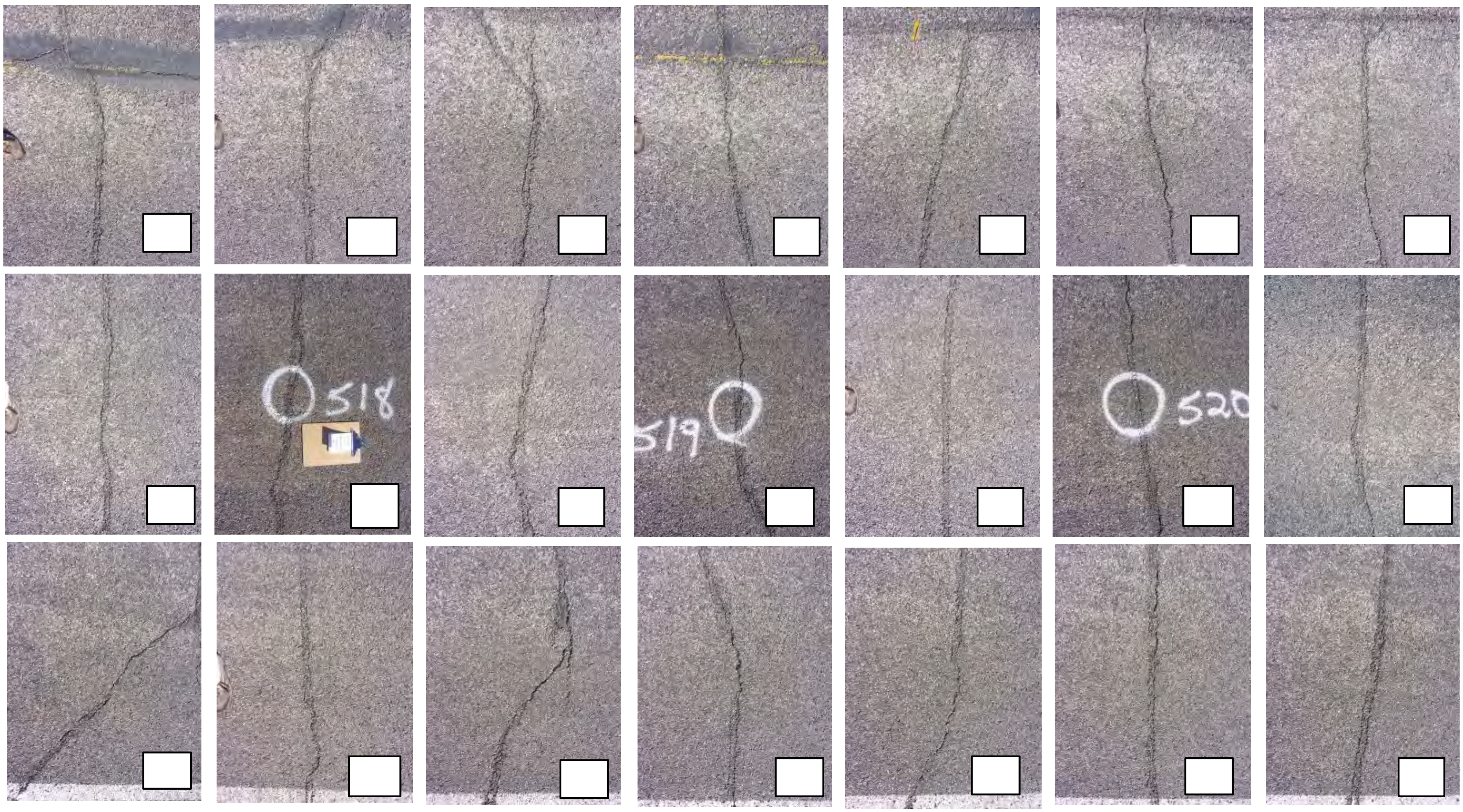
Road Saver 231SD (Crafco), Highmore Site, Inspection 3

			Installation 9/6/2017, 2:30pm			Inspection 3 3/21/19	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
2246	59	38	68	119	380		
2237	✓with MRM values						



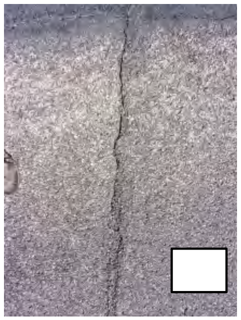
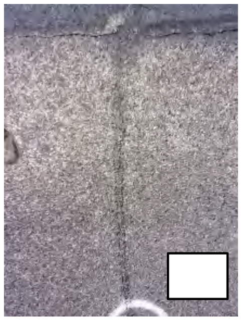
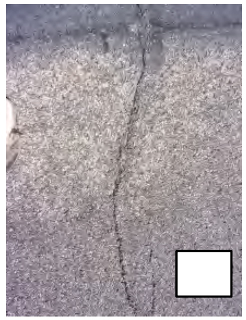
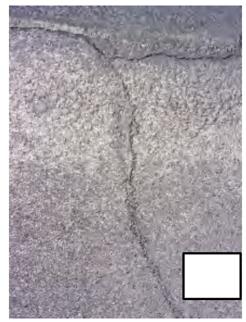
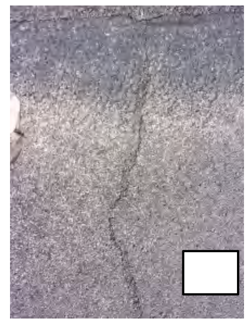
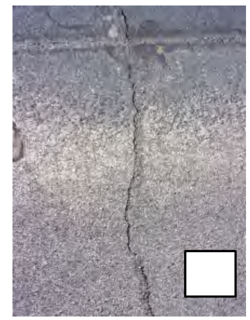
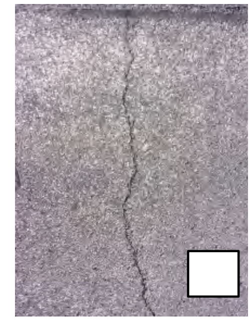
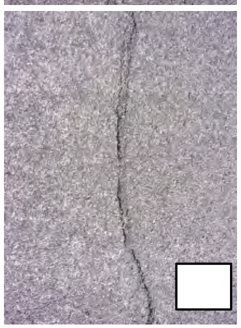
101 ELT (Deery), Highmore Site, Inspection 3

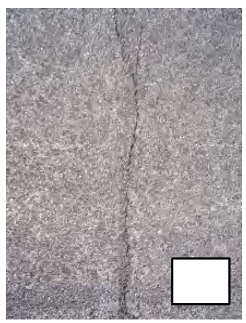
			Installation 9/6/2017			Inspection 3 3/21/19	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
2016	70	29	65	111	370		
2011	✓with MRM values						

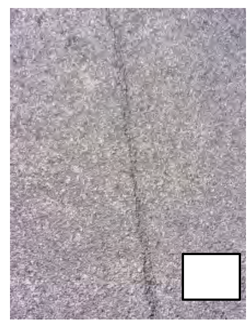


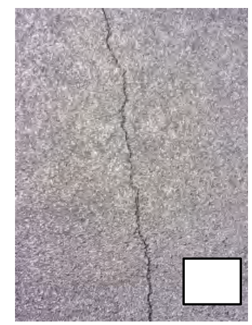
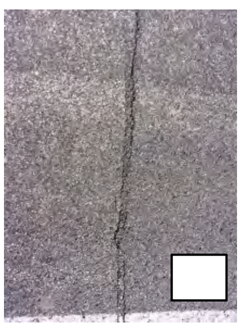
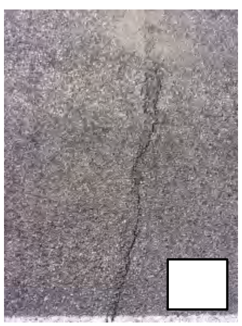
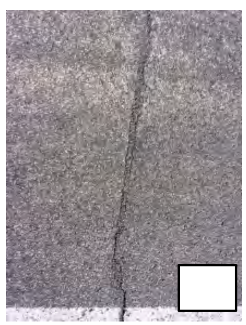
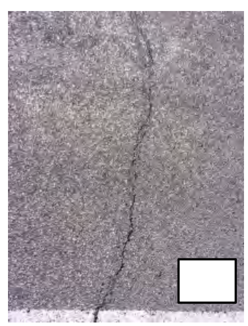
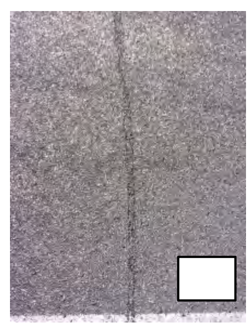
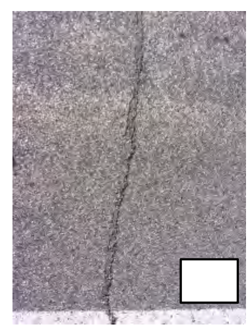
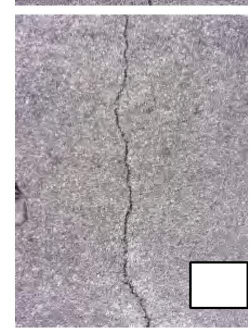
McAsphalt 6690 (Macseal), Highmore Site, Inspection 3

			Installation 9/6/2017, 4:30pm			Inspection 3 3/21/19	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
1550	58	27	60	115	365		
1561	✓with MRM values						

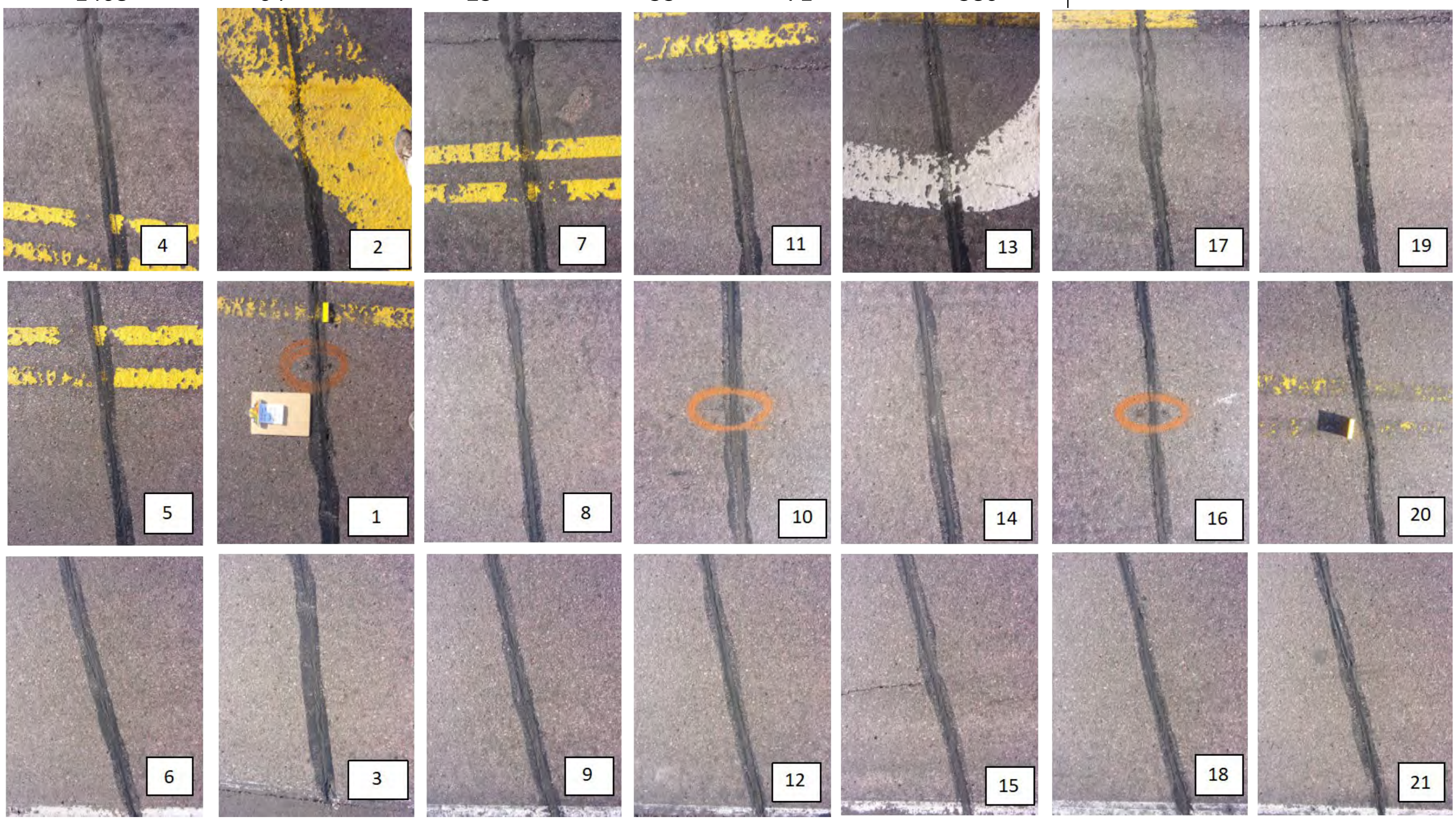



Road Saver 231SD (Crafco), Yankton Site, Inspection 3

Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Installation 9/7/2017, 9:15am			Inspection 3 3/22/19	
			Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
1468	64	23	53	71	380		



McAsphalt 6690 (Macseal), Yankton Site, Inspection 3

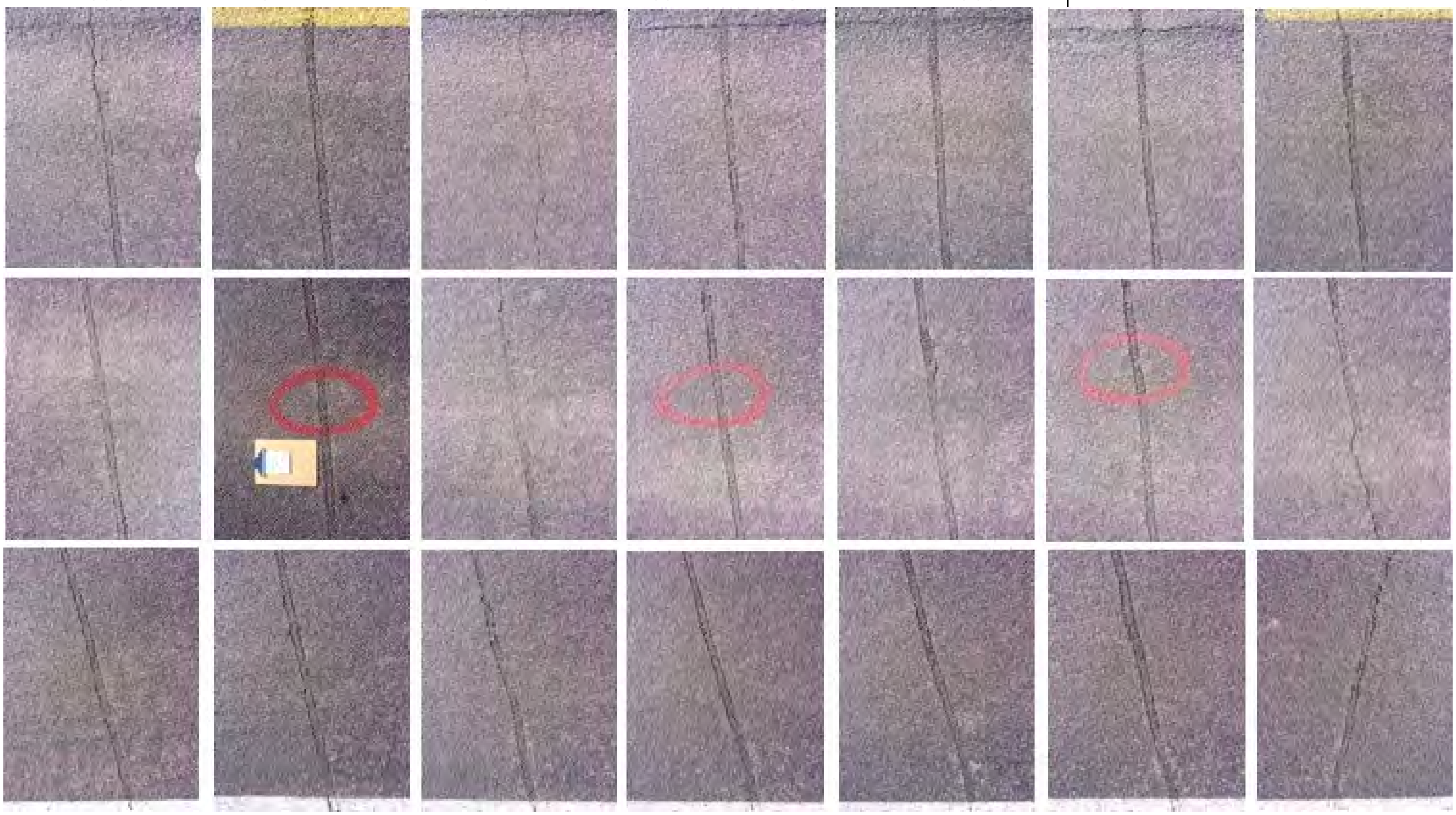
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Installation 9/7/2017, 9:30am Air Temp	Pavement Temp	Kettle Temp	Inspection 3 3/22/19 Air Temp	Pavement Temp
1346	62	22	55	74	380		

101 ELT (Deery), Yankton Site, Inspection 3

Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Installation 9/7/2017, 10:30am Air Temp	Installation 9/7/2017, 10:30am Pavement Temp	Installation 9/7/2017, 10:30am Kettle Temp	Inspection 3 3/22/19 Air Temp	Inspection 3 3/22/19 Pavement Temp
1309	73	18	59	74	385		

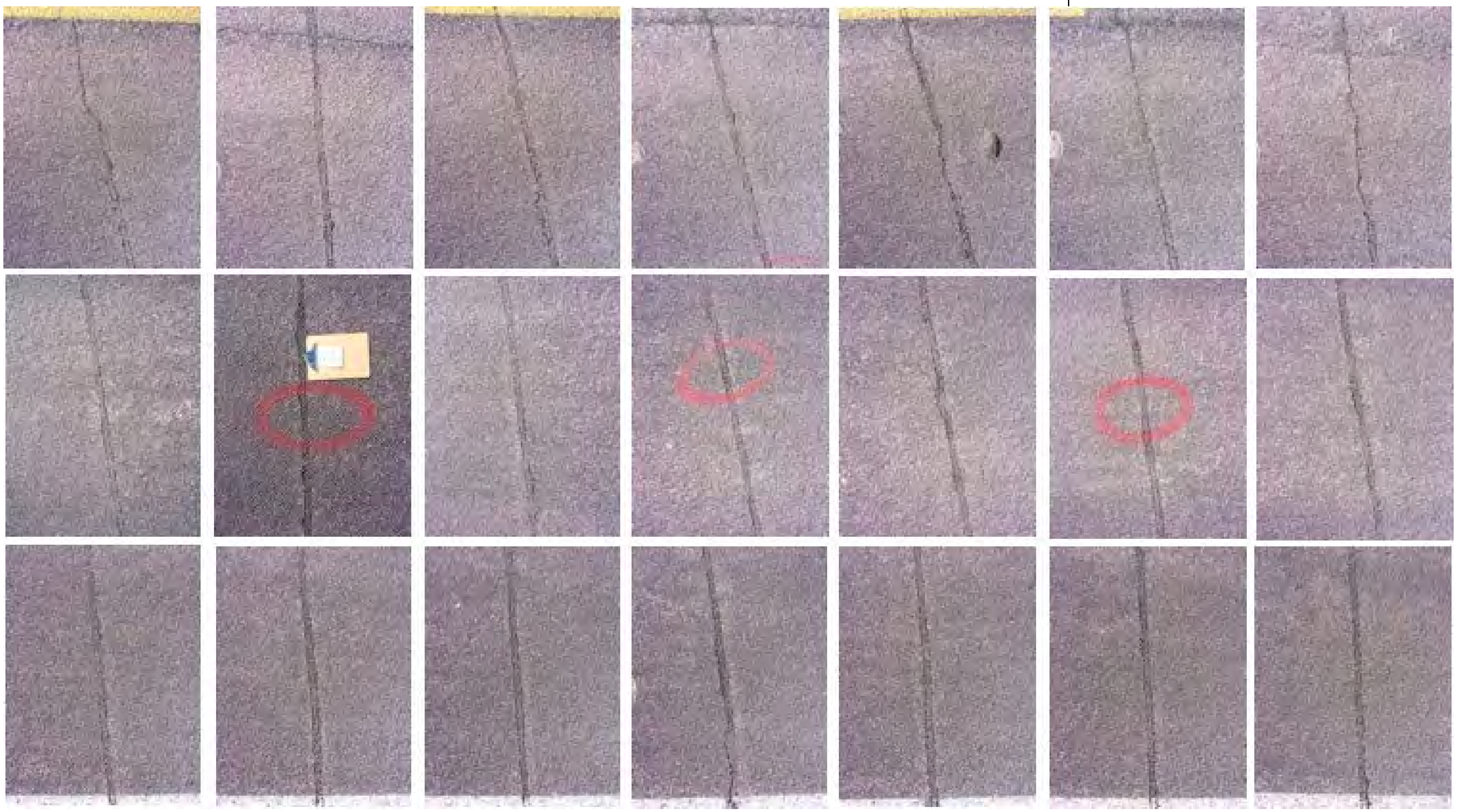
Road Saver 522 (Crafco), Yankton Site, Inspection 3

Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Installation 9/7/2017, 11:00am			Inspection 3 3/22/19	
			Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
1595	87	18	69	87	365		



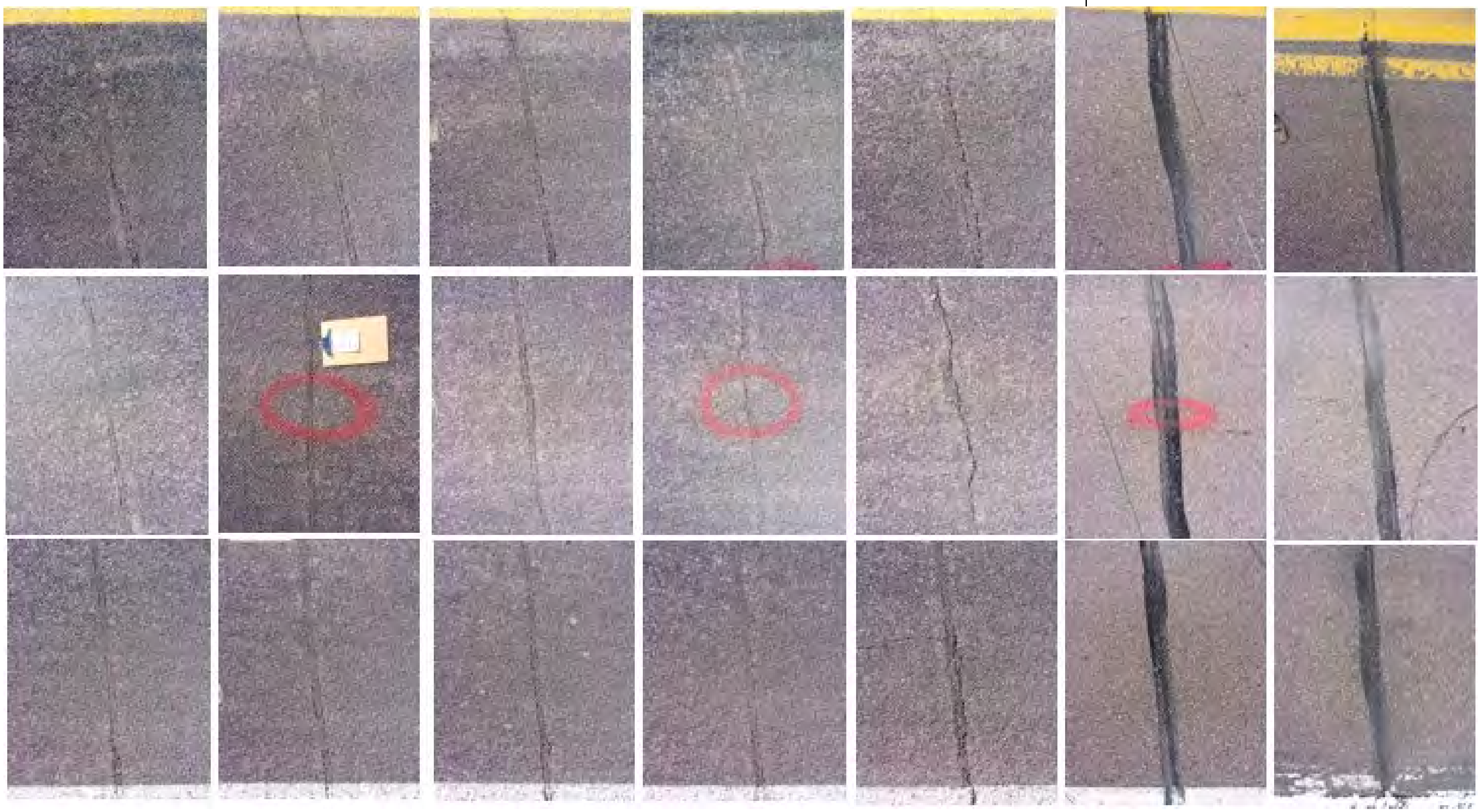
Mod 4 3405 (Right Pointe), Yankton Site, Inspection 3

			Installation 9/7/2017, 3:00pm			Inspection 3 3/22/19	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
2144	62	35	73	114	350		



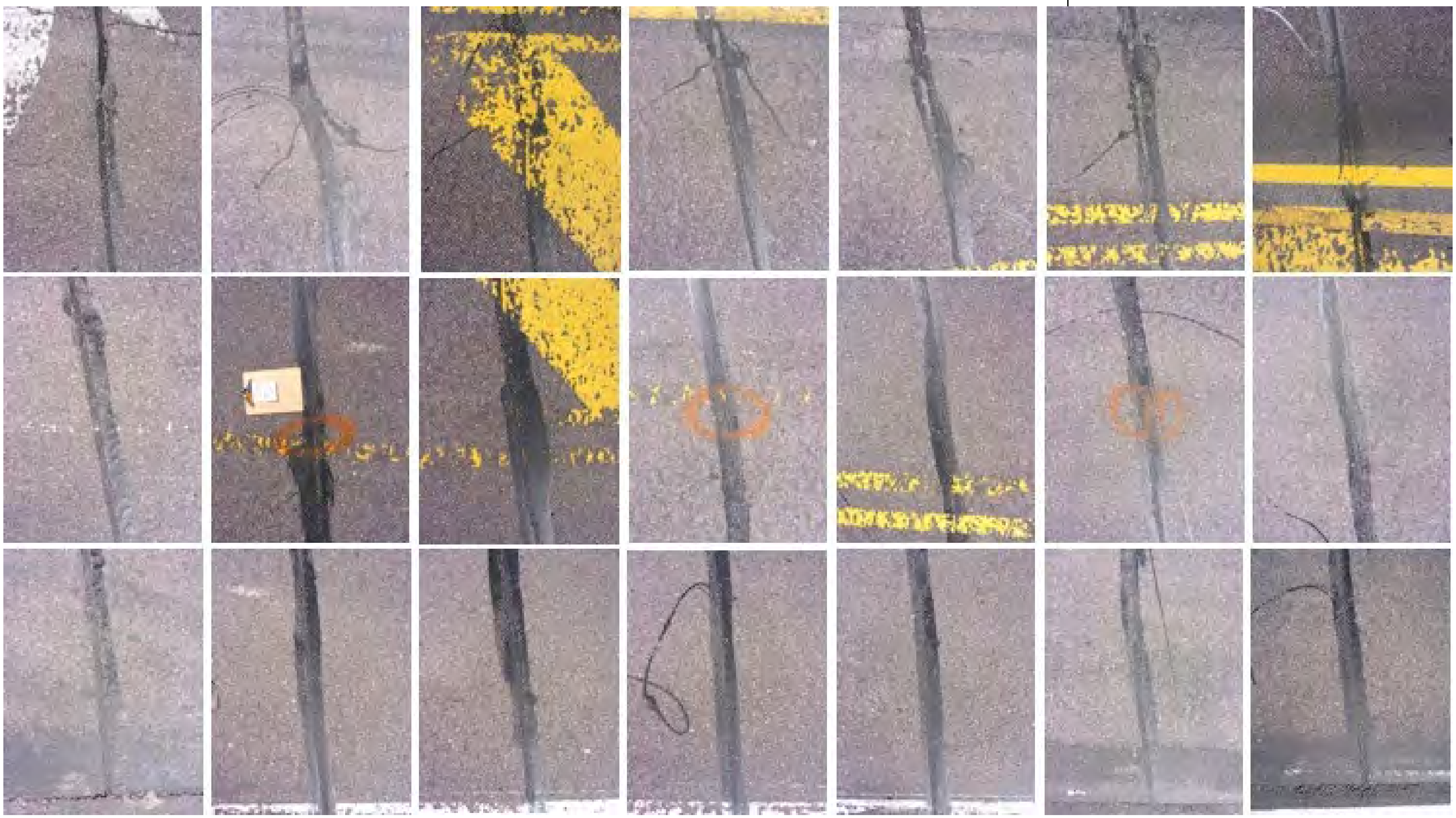
Deery 101 SD, Yankton Site, Inspection 3

			Installation 9/7/2017, 3:00pm			Inspection 3 3/22/19	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
1774	63	28	73	114	350		



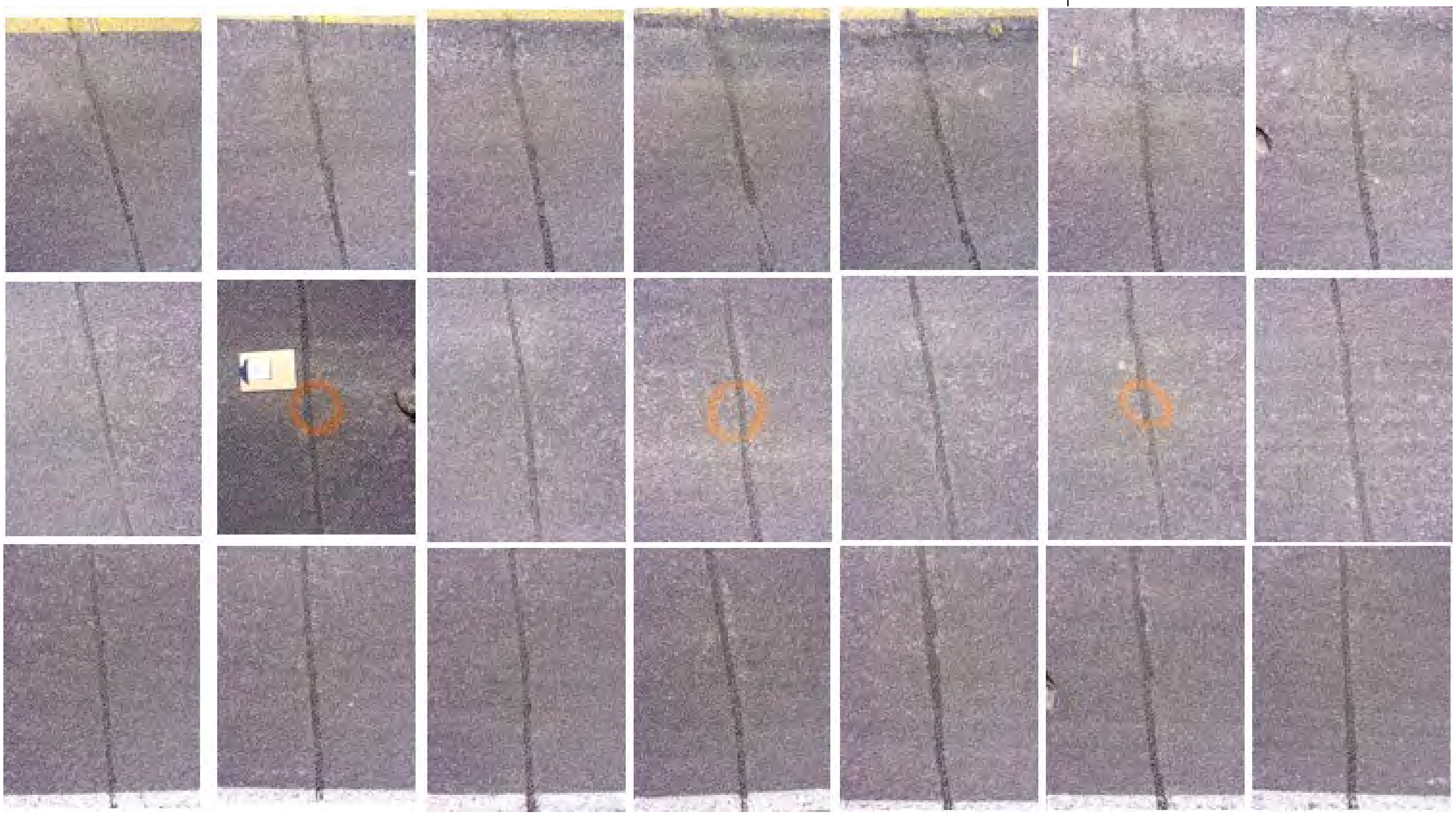
Elastoflex 72 (Maxwell), Yankton Site, Inspection 3

			Installation 9/7/2017, 3:00pm			Inspection 3 3/22/19	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
1964	56	35	73	114	350		



3405 M (WR Meadows), Yankton Site, Inspection 3

			Installation 9/7/2017, 3:00pm			Inspection 3 3/22/19	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
1848	101	18	73	114	350		



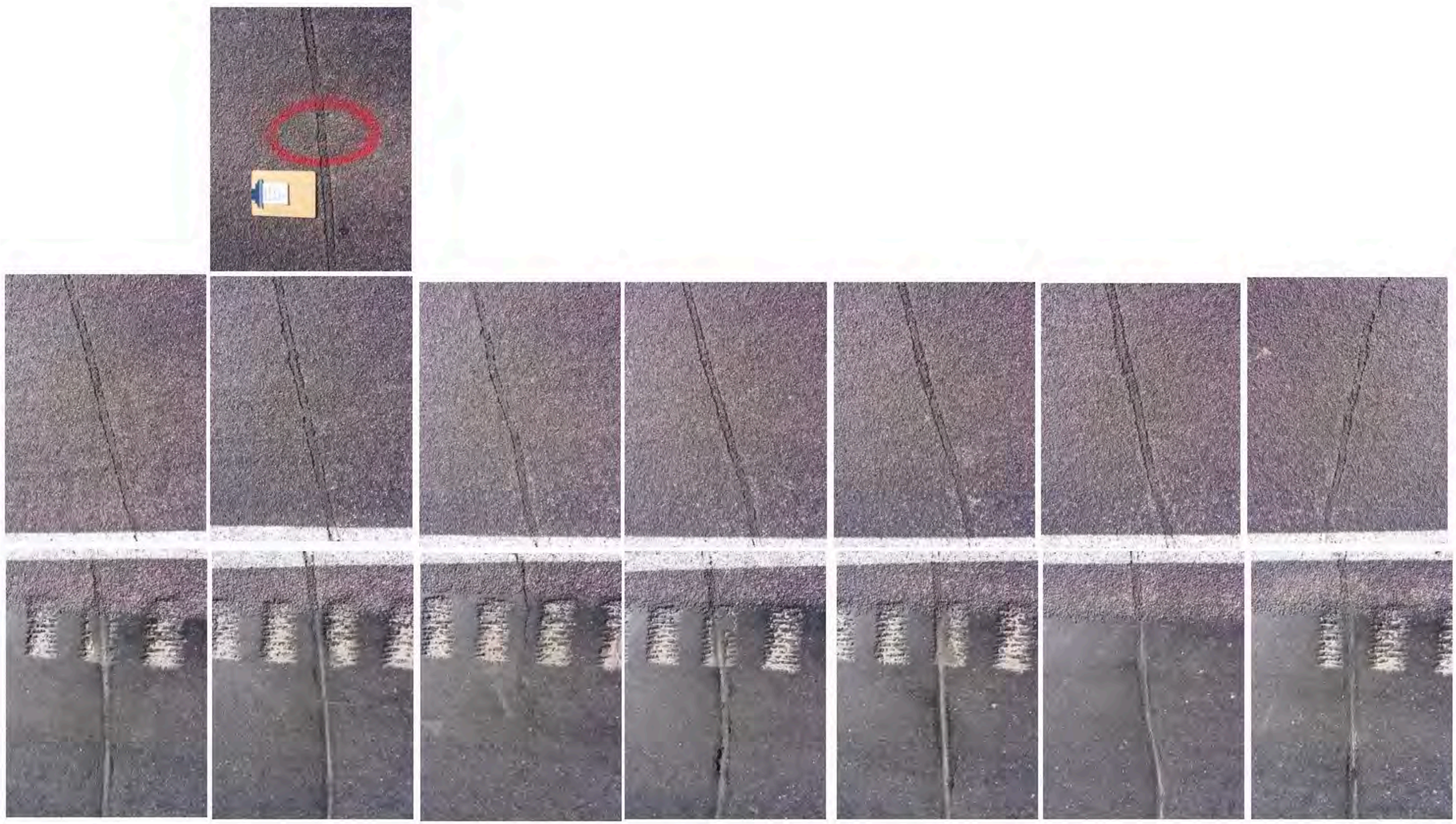
APPENDIX H CRACK AND SEALANT PHOTOGRAPHS; SECOND WINTER INSPECTION WITH SHOULDERS

101 ELT (Deery), Yankton Site, Inspection 3

			Installation 9/7/2017, 10:30am			Inspection 3 3/22/19	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
1309	73	18	59	74	385		

Road Saver 522 (Crafco), Yankton Site, Inspection 3

			Installation 9/7/2017, 11:00am			Inspection 3 3/22/19	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
1595	87	18	69	87	365		

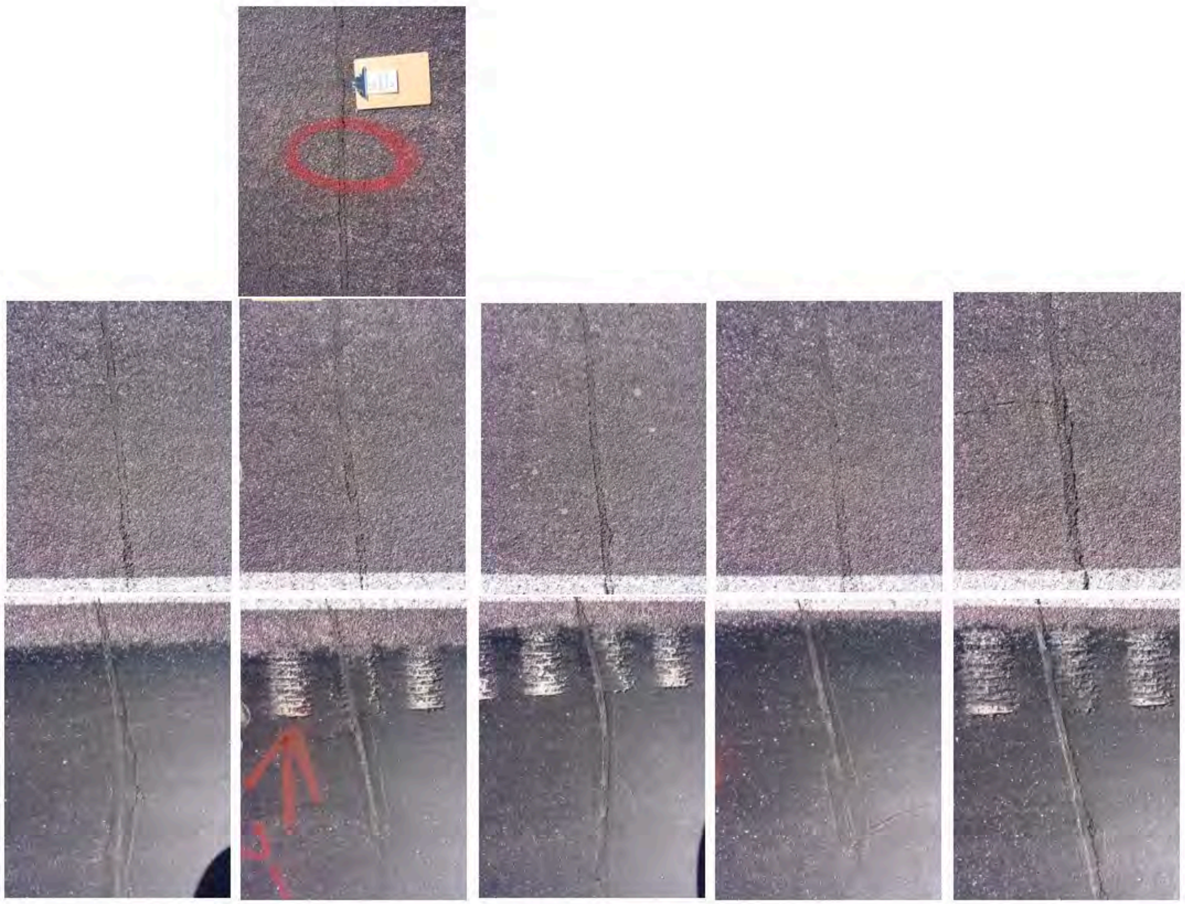


Mod 4 3405 (Right Pointe), Yankton Site, Inspection 3

			Installation 9/7/2017, 3:00pm			Inspection 3 3/22/19	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
2144	62	35	73	114	350		

Deery 101 SD, Yankton Site, Inspection 3

Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Installation 9/7/2017, 3:00pm Air Temp	Installation 9/7/2017, 3:00pm Pavement Temp	Installation 9/7/2017, 3:00pm Kettle Temp	Inspection 3 3/22/19 Air Temp	Inspection 3 3/22/19 Pavement Temp
1774	63	28	73	114	350		



3405 M (WR Meadows), Yankton Site, Inspection 3

			Installation 9/7/2017, 3:00pm			Inspection 3 3/22/19	
Test Section Length (ft)	Number of cracks	Approximate crack spacing (ft)	Air Temp	Pavement Temp	Kettle Temp	Air Temp	Pavement Temp
1848	101	18	73	114	350