VTRC
Virginia Transportation
Research Council

We Bring Innovation to Transportation

Validation of Hot-Poured Crack Sealant Performance-Based Guidelines

http://www.virginiadot.org/vtrc/main/online_reports/pdf/17-r26.pdf

IMAD L. AL-QADI, Founder Professor of Engineering
Director, Illinois Center for Transportation
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

HASAN OZER, Research Assistant Professor
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

SEYED SALEH YOUSEFI, Graduate Research Assistant
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

MOHAMMED SAWALHA, Graduate Research Assistant
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

KEVIN K. McGHEE, Principal Research Scientist
Virginia Transportation Research Council

Final Report VTRC 17-R26

VIRGINIA TRANSPORTATION RESEARCH COUNCIL
530 Edgemont Road, Charlottesville, VA 22903-2454
vtrc.virginiadot.org

Standard Title Page - Report on Federally Funded Project

1. Report No.: FHWA/VTRC 17-R26	2. Government Accession No.:	3. Recipient’s Catalog No.:

4. Title and Subtitle:
Validation of Hot-Poured Crack Sealant Performance-Based Guidelines

5. Report Date:
June 2017

6. Performing Organization Code:

7. Author(s):
Imad L. Al-Qadi, Hasan Ozer, Seyed Saleh Yousefi, Mohammed Sawalha, and Kevin K. McGhee

8. Performing Organization Report No.:
VTRC 17-R26

9. Performing Organization and Address:
Virginia Transportation Research Council
530 Edgemont Road
Charlottesville, VA 22903

10. Work Unit No. (TRAIS):

11. Contract or Grant No.:
98160

12. Sponsoring Agencies’ Name and Address:

Virginia Department of Transportation	Federal Highway Administration
1401 E. Broad Street	400 North 8th Street, Room 750
Richmond, VA 23219	Richmond, VA 23219-4825

13. Type of Report and Period Covered:
Final Contract

14. Sponsoring Agency Code:

15. Supplementary Notes:

16. Abstract:

This report summarizes a comprehensive research effort to validate thresholds for performance-based guidelines and grading system for hot-poured asphalt crack sealants. A series of performance tests were established in earlier research and include the crack sealant bending beam rheometer (CSBBR), crack sealant direct tension test (CSDTT), the crack sealant adhesion test (CSAT), a rotational viscosity test, and a dynamic shear test. Validation was accomplished through an extensive field performance study incorporating a wide spectrum of commonly used sealants installed in eight test sites around the United States using two basic treatment methods: (1) clean and seal, and (2) rout and seal. Performance of these sealants and treatment methods were monitored for 3 years to quantify relative performance, primarily through adhesive and cohesive failures, as well as overband wear. Field samples were also collected from the sites to conduct laboratory testing to reflect in-service properties. A statistical method was used to develop correlations of the tests parameters with the field performance. The composite score approach, combining ranking and correlation, was used to develop a quantitative scale for determining the level of acceptance. Based on the composite score, a strong or acceptable correlation was obtained between field performance and laboratory test parameters. After the correlation between field performance and lab results was confirmed, the thresholds for test methods were selected or fine-tuned.

An investigation was also conducted to evaluate the short-term and long-term aging effects of hot-poured crack sealants through a differential aging test. Rheological and mechanical properties of sealants at different aging stages were monitored to characterize the aging effects. Laboratory aging of sealants was studied using three different aging methods: kettle aging, melter aging, and vacuum oven aging (VOA). The aging index was used to evaluate the effect of these aging methods. By a comparison of the stiffness master curves obtained from the CSBBR test for field-aged samples and laboratory-aged samples, VOA was validated as a reasonable aging method for simulating 2 to5 years of field aging.

The research proposes new guidelines for full implementation as AASHTO specifications. In addition to validated and revised thresholds for existing protocols, the research proposed a modified adhesion test and a simplified test for tracking resistance. Close inspection of the installation techniques and early performance feedback also supported the development of guidelines for crack sealant installation and application.

17 Key Words:
Hot-poured crack sealant, rheology, field performance, sealant grade, CSBBR, CSDTT, CSAT, DSR, RV, Aging

18. Distribution Statement:
No restrictions. This document is available to the public through NTIS, Springfield, VA 22161

19. Security Classif. (of this report):	20. Security Classif. (of this page):	21. No. of Pages:	22. Price:
Unclassified	Unclassified	70	

FINAL REPORT

VALIDATION OF HOT-POURED CRACK SEALANT PERFORMANCE-BASED GUIDELINES

Imad L. Al-Qadi
Founder Professor of Engineering
Director, Illinois Center for Transportation
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

Hasan Ozer
Research Assistant Professor
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

Seyed Saleh Yousefi
Graduate Research Assistant
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

Mohammed Sawalha
Graduate Research Assistant
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

Kevin K. McGhee
Principal Research Scientist
Virginia Transportation Research Council

Project Manager
Kevin K. McGhee, P.E., Virginia Transportation Research Council

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

June 2017
VTRC 17-R26

DISCLAIMER

The project that is the subject of this report was done under contract for the Virginia Department of Transportation, the Virginia Transportation Research Council. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. Any inclusion of manufacturer names, trade names, or trademarks is for identification purposes only and is not to be considered an endorsement.

Each contract report is peer reviewed and accepted for publication by staff of the Virginia Transportation Research Council with expertise in related technical areas. Final editing and proofreading of the report are performed by the contractor.

ABSTRACT

This report summarizes a comprehensive research effort to validate thresholds for performance-based guidelines and grading system for hot-poured asphalt crack sealants. A series of performance tests were established in earlier research and include the crack sealant bending beam rheometer (CSBBR), crack sealant direct tension test (CSDTT), the crack sealant adhesion test (CSAT), a rotational viscosity test, and a dynamic shear test. Validation was accomplished through an extensive field performance study incorporating a wide spectrum of commonly used sealants installed in eight test sites around the United States using two basic treatment methods: (1) clean and seal, and (2) rout and seal. Performance of these sealants and treatment methods were monitored for 3 years to quantify relative performance, primarily through adhesive and cohesive failures, as well as overband wear. Field samples were also collected from the sites to conduct laboratory testing to reflect in-service properties. A statistical method was used to develop correlations of the tests parameters with the field performance. The composite score approach, combining ranking and correlation, was used to develop a quantitative scale for determining the level of acceptance. Based on the composite score, a strong or acceptable correlation was obtained between field performance and laboratory test parameters. After the correlation between field performance and lab results was confirmed, the thresholds for test methods were selected or fine-tuned.

An investigation was also conducted to evaluate the short-term and long-term aging effects of hot-poured crack sealants through a differential aging test. Rheological and mechanical properties of sealants at different aging stages were monitored to characterize the aging effects. Laboratory aging of sealants was studied using three different aging methods: kettle aging, melter aging, and vacuum oven aging (VOA). The aging index was used to evaluate the effect of these aging methods. By a comparison of the stiffness master curves obtained from the CSBBR test for field-aged samples and laboratory-aged samples, VOA was validated as a reasonable aging method for simulating 2 to5 years of field aging.

The research proposes new guidelines for full implementation as AASHTO specifications. In addition to validated and revised thresholds for existing protocols, the research proposed a modified adhesion test and a simplified test for tracking resistance. Close inspection of the installation techniques and early performance feedback also supported the development of guidelines for crack sealant installation and application.

FINAL REPORT

VALIDATION OF HOT-POURED CRACK SEALANT PERFORMANCE-BASED GUIDELINES

Imad L. Al-Qadi
Founder Professor of Engineering
Director, Illinois Center for Transportation
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

Hasan Ozer
Research Assistant Professor
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

Seyed Saleh Yousefi
Graduate Research Assistant
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

Mohammed Sawalha
Graduate Research Assistant
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

Kevin K. McGhee
Principal Research Scientist
Virginia Transportation Research Council

INTRODUCTION

Crack sealing is widely accepted as a cost-effective, routine, and preventive maintenance practice that extends pavement service life 3 to 5 years when properly installed. Hot-poured asphalt crack sealant keeps its shape as applied and hardens through chemical and/or physical processes to form a viscoelastic rubber-like material that withstands extension or compression due to crack movements and weathering effects. Some of the essential properties of sealants, such as extendibility, cohesiveness, and adhesive characteristics, are needed to ensure good performance. Sealants, when properly selected and installed, can remain functional for 3 to 5 years. Therefore, the selection of a proper crack sealant for a particular environment and pavement is essential to guarantee its performance.

The standards and specifications currently used to select crack sealants were established based on material properties that are generally empirical and do not measure sealant fundamental properties. Also, the specification limits vary from one state to another. These differences create difficulties for crack sealant suppliers because many states with the same environmental conditions specify different limits for the measured properties. The current standard tests are also reported to correlate poorly with the rheological properties of bituminous-based crack sealants and often fail to predict sealant performance in the field.

Recently, performance-based guidelines were developed as a systematic procedure to select hot-poured bituminous crack sealants (Al-Qadi et al., 2009). These guidelines are the outcome of the pooled-fund North American Consortium led by the University of Illinois at Urbana-Champaign and the National Research Council of Canada. The sponsoring consortium included 11 U.S. state departments of transportation, 13 Canadian transportation agencies, and industry. The U.S. contribution was made through Pooled Fund Research Project TPF-5(045), which was led by the Virginia Department of Transportation (VDOT) / Virginia Transportation Research Council (VTRC). The work proposed a "Sealant Grade" (SG) system to select hot-poured crack sealant based on environmental conditions. A special effort was made to use the equipment originally developed by the Strategic Highway Research Program (SHRP), which was used to measure binder rheological behavior as part of the binder Performance Grade (PG) system. The equipment, specimen preparation, and testing procedure were modified in accordance with crack sealant behavior. In addition, new tests for sealant aging and sealant evaluation were introduced. The developed laboratory tests allow for measuring hot-poured asphalt crack sealants rheological and mechanical properties over a wide range of service temperatures. Preliminary thresholds for each test were identified to ensure desirable field performance.

PURPOSE AND SCOPE

The preliminary thresholds were determined based on limited field data only and, therefore, a comprehensive field study was urgently needed to validate and fine-tune the initially proposed threshold values. Hence, in this study, an extensive field study was designed to validate and fine-tune the threshold values. The purpose of this study was to achieve the following goals: (1) validate the developed laboratory tests using field performance; (2) determine the thresholds using a more diverse array of field performance data; and (3) develop guidelines for crack sealant installations and applications. The scope of this study included installation of test sites, evaluation of the field performance, and correlation to AASHTO laboratory performance tests. Finally, new guidelines were developed and validated for full implementation as AASHTO specifications.

METHODS

Overview of Experimental Program

To meet the objectives of this study, the methodology presented in Figure 1 was executed. The experimental program consists of two major tasks: field performance evaluation of crack sealants, and laboratory characterization. Eighteen sealants were installed in six different test sites. All test sites were selected in collaboration with participating state departments of transportation in different environmental regions in North America. A wide spectrum of materials was installed in these test sites. Test sites were all wet-freeze climatic zones, except for one wet-no freeze zone with some variations in temperature fluctuations. Two commonly used sealing techniques were implemented: (1) rout and seal, and (2) clean and seal. Rout and seal treatments were applied with varying reservoir geometry. Clean and seal treatments were also applied at the same locations to facilitate comparisons between the two sealing techniques. In order to eliminate any bias in the performance, installations were monitored closely while recording as much data as possible before, during, and after installation.

Field performance data collection was conducted annually to collect logged temperature data, assess performance (types of crack sealant failure), and gather field-aged samples. Then, the field-aged samples were tested in the laboratory to characterize their low-temperature properties. Both field performance data and lab results were analyzed using statistical methods and compared to one another. Once a satisfactory correlation was achieved, using laboratory test results, parameters were calculated at the actual test site temperature that the materials experienced in the field. The results at the actual field temperature were used to fine-tune the initial threshold values, if needed. The final threshold values were selected by comparing the lab measured parameters with the field performance using an iterative approach that yielded consistent ranking and correlation between field performance and laboratory test results. Detailed steps of the methodology are explained in the following sections.

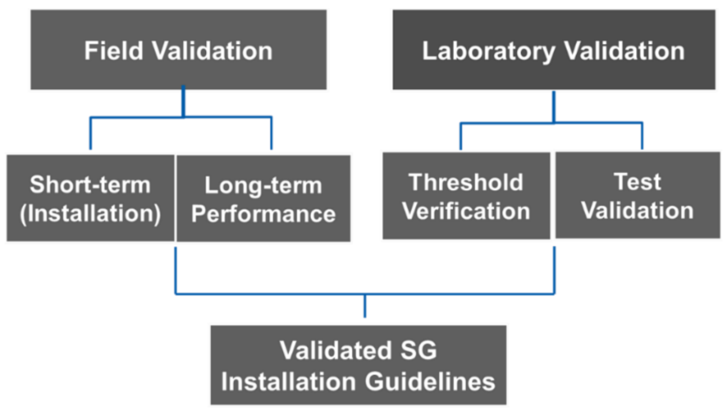


Figure 1. Experimental Program Used to Validate and Fine-Tune Provisional AASHTO Test Methods for Selection of Hot-Poured Crack Sealants

Field Validation

Site Selection

For successful sealant treatment and performance evaluation, selection of candidate pavements and condition of cracks should be given significant attention. Pavements with sufficient structural strength and good rideability were considered as candidate test sites. The typical pavement condition rating used in “Guidelines for Sealing and Filling Cracks in Asphalt Concrete Pavements” (Masson et al., 2003) were used as guidelines for the selection of test sites. According to these guidelines, crack sealing applies to pavements in good condition with a smooth riding surface. Therefore, pavements in good or fairly good condition with cracks in relatively good condition were selected as test sites.

The candidate transverse cracks were full-lane width cracks with minimal edge deterioration (i.e., spalls and secondary cracks). The criteria used for the selection of candidate test sections are similar to those presented by Masson (2001). The following summarizes these criteria:

- Cracks should be less than 15 mm wide.
- Cracks should not be a part of a web of cracks.
- Cracks should show little or no branching.
- Cracks should not have any severe vertical distress, such as lipping or cupping.

Four of the test sections were identified in the first year of the project (2011) and installations were completed for those sections. All sections are located in a wet-freeze climatic zone. Two more test sites were added to the experimental matrix in the second year (2012) and fourth year (2014). The fourth year test site was located in a dry-no freeze climatic zone. Table 1 summarizes the test sections and relevant parameters considered in the selection of each test section. Test site installations were performed in six states between June 2011 and January 2014.

Table 1. Test Site Summary and Parameters Considered in the Selection of Field Experimental Plan

Test Site Location	Climatic Region	Min/Max Temperature (°C)	Traffic	Initial Pavement Condition	Pavement Type	Installation Date
Belleville, Wisconsin	Wet-Freeze	-29/32	2,000 AADT with 6% Truck	11 years old[2] in fair condition with longitudinal and transverse cracks	HMA	7/19/2011
St Charles, Minnesota	Wet-Freeze	-31/31	13,055 ADT	2 years old in good condition with transverse reflective cracking	HMA Overlay on Jointed PCC	9/11/2011
Lindsay, Ontario, CA	Wet-Freeze	-29/30	9,022 AADT with 7.5% Truck	13 years old in fair condition with transverse and some long. Cracks	HMA	9/20/2011
Grantham, New Hampshire	Wet-Freeze	-29/32	9,500 AADT with 9% Truck	2 years old in good condition with transverse reflective cracking	HMA over PCC	10/3/2011
Canandaigua, New York	Wet-Freeze	-24/31	6,600 AADT with 5% Truck	2 years old in very good condition with transverse reflective cracking	HMA over PCC	9/11/2012
Roscommon County, Michigan	Wet-Freeze	-29/30	N/A	N/A	HMA	10/11/2010
Salem, Virginia	Wet-Freeze	-16/34	N/A	N/A	HMA	9/29/2014
Champaign, Illinois[1]	Wet-Freeze	-24/34	No Traffic	N.A	HMA	09/15/2011

[1] This section was designed and installed to investigate field aging mechanisms and weathering.
[2] Pavement age is calculated at the time of installation.

Test Matrix

Following the selection of sealants, a testing plan was prepared for each test site. The sealants were distributed to the test sites with approximately five to seven sealants installed at each test site (Table 2). The distribution of sealants to each site was determined based on the following criteria: (1) installation of a sealant material at a minimum of two different sections for repeatability; (2) a spectrum of material properties to ensure significant differences in field performance; and (3) agencies' request to include a specific product in the test matrix. Table 2 summarizes the test matrix that was ultimately finalized and constructed.

Once the test sites and materials were selected and determined, a site-dependent test plan was proposed. The test plans considered specific site characteristics such as pavement condition, number of transverse cracks available, crack spacing, availability of traffic control, and length of test section. A test matrix was prepared with the proposed sealants and the test parameters deemed critical for field performance, including sealant type, crack treatment type, rout geometry, and overbanding. An overview of the test plan for each test site is shown in Table 3.

Table 2. Distribution of Materials to the Test Sites

ID	ASTM Type	SG (AASHTO TP -xx)	Minnesota	New Hampshire	Wisconsin	New York	Ontario	Virginia	Total Repetitions
Ad	IV	70-40	X		X				2
Bb	II	64-16	X		X		X		3
Ca	I	70-10				X			1
Da	I	76-34				X	X		2
Ed	IV	76-40		X	X			X	3
Fb[2]	II	-34	X	X	X				3
Gd	IV	76-34	X	X			X		3
Hb[2]	II	-22	X					X	2
Ib[2]	II	-10				X		X	2
Lb[1]	II	NA						X	1
Jd	IV	70-46				X			1
Kc[2]	III	-28		X		X			2
Mb[2]	II	-34	X				X		2
Nb[2]	II	-34	X						1
Ob	II	82-40		X		X			2
Pd	IV	64-28			X		X		2
Rb[1]	II	NA					X		1
Sd	IV	76-34					X		1

[1]Virgin material for sealants Lb and Rb was not available to be aged and graded in the laboratory.
[2]These sealants are only graded at low temperature.

Table 3. Site-Specific Experimental Plan for Field Investigation of Sealant Performance

Test Site	Climatic Region	Crack Treatment Variables	Reservoir Geometry (mm)	Materials
Wisconsin	Wet-Freeze	Crack Seal only	20 x 20	Five materials from three different manufacturers
Minnesota	Wet-Freeze	Crack Seal & Fill, Variable Rout Size	12.5 x 12.5 20 x 20 30 x 15	Seven materials from three different manufacturers
Ontario	Wet-Freeze	Crack Seal & Fill, Variable Rout Size	20 x 20 12.5 x 12.5 30 x 15 40 x 10	Seven materials from four different manufacturers
New Hampshire	Wet-Freeze	Crack Seal & Fill, Variable Rout Size	12.5 x 12.5 20 x 20 30 x 15	Five materials from three different manufacturers
New York	Wet-Freeze	Crack Seal & Fill, Variable Rout Size	12.5 x 12.5 20 x 20 30 x 15	Eight materials from four different manufacturers
Virginia	Wet-Freeze	Crack Seal & Fill	20 x 20	Four materials from same manufacturer
Michigan	Wet-Freeze	Crack Fill only	NA	Sixteen materials from seven different manufacturers

Site Preparation and Preliminary Survey

Prior to the installation of sealants, a series of tasks were performed, including preliminary detailed survey of the test site, installation of displacement pins, and finalization of the test plan based on on-site conditions. The preliminary tasks are summarized in detail hereafter.

Baseline Conditions

A preliminary survey was conducted at the test sites prior to installation in order to collect information about the initial condition of pavement and cracks. Each test site was surveyed rigorously to determine crack spacing, number of cracks, crack rating, station numbering, and photo documentation. A rating system was developed to document the initial condition of the cracks. The rating system is a qualitative measurement based on visual inspection. The cracks were rated based on their initial condition (partial- or full-length crack, branching severity, and crack width and depth) and their suitability for sealing. Ratings from 1 to 5 were assigned to cracks with 5 indicating best condition per the selection criteria (full-length crack, no branching, <10 mm opening), and 1 indicating worst condition. Cracks with ratings below 3 were not evaluated for performance in this study; however, they were considered for field sampling. Figure 2 shows images from two different test sites.

Figure 2. Initial Survey and Crack Numbering of a Test Section

Based on the preliminary survey, a summary of pavement and initial crack conditions is provided in Table 4. In general, the selected test sections were in favorable conditions for crack sealing and filling. Variation in crack spacing also allowed for evaluation of the influence of crack displacements on sealant performance.

Table 4. A Summary of Preliminary Survey Results

Test Site	**Average Crack Spacing (m)**	**Number of Cracks**	**Average Crack Rating (1: worst and 5: best)**
Wisconsin	17.5	156	3.3
Minnesota	11.5	225	4.6
Ontario	30	276	3.5
New Hampshire	21.5	234	4.7
New York	39	181	3.7
Virginia	15.5	137	2.8

Crack Displacement Pin Installation

Crack displacement is one of the most critical parameters influencing sealant performance. Opening and closing of cracks can be a function of temperature, crack spacing, pavement structure, and materials. Crack displacements were measured at each test site using stainless steel pins driven on each side of the crack. Approximately 30 cracks were pinned at each test site to monitor displacements. Pin installation included drilling a 6 mm hole, filling the hole with rapid setting epoxy and driving the pin in the hole. Pins were installed at the edge, mid-lane, and center lane locations. Measurements were taken using conical-end calipers. Initial measurements were recorded right after installation. Figure 3 shows two cracks at a test site with single- and triple-point displacement pins.

Figure 3. Crack Displacement Pins: Single-Point to Measure Only Right Wheel Path (left) and Three-Point to Measure Both Wheel Path and Middle of the Lane (right)

Test Site Installations

This section summarizes test site installations conducted between 2011 and 2014. A brief overview of each test site, data collected during installation, and highlights of the installation process are presented herein.

Wisconsin Test Site

The Wisconsin test site is located in Green County on State Highway 92. The test sections were selected from a 17.5 km pavement section between Brooklyn and Belleville. The total length of sections where test sealants were installed is 2.9 km. This pavement section was constructed in 2000 and consists of 10 cm asphalt concrete overlay on 15 cm asphalt concrete supported by crushed aggregate base. Shoulders were paved with 8 cm thick asphalt concrete on 30 cm thick gravel base. The section is a two-lane highway; each lane is 3.5 m wide. The sealants were installed on July 19 through21, 2011. The Green County Highway Department controlled traffic and installed the sealants. This test site was partitioned into five sections for installing five different sealants. Standard rout geometry (20 x 20 mm) was used in the entire test site.

Minnesota Test Site

The Minnesota test site is located on Interstate 90 in the St. Charles area. The test sections are located on westbound I-90 between Mileposts 235 and 238. The total length of the section is 2.9 km with the test sections in the driving lane. The section was overlaid in 2009 with 11 cm thick asphalt concrete on a jointed PCC. It consists of two lanes in each direction; each is 3.6 m wide. The shoulder width is 3 m throughout the entire test section. Installation took place during the week of September 11, 2011. This test site consisted of 24 sections including seven sealants that were installed using various treatment methods. Reflective transverse cracking was found to be the main crack type in this test site.

Ontario Test Site

The Ontario test site is located on Highway 35 in the Lindsay area. The test site starts 140 m south of Bethany Hills Rd on Highway 35 and ends at around 6.1 km south of the

Highway 7 junction. The total length of the section is 8.9 km. The section was rehabilitated in 1998 using full-depth reclamation with a 25-mm-thick asphalt concrete overlay. It consists of two lanes; each lane is 3.2 m wide. The shoulders were partially paved and are 1 m wide. The sealant was installed in the week of September 20, 2011. This test site consists of 16 sections within which seven sealants were installed using various treatment methods.

New Hampshire Test Site

The New Hampshire test site is located on I-89 in the Grantham area. The test sections are on both southbound and northbound I-89. The southbound sections start at Milepost 48.0 and end at around Milepost 46.2. The northbound sections extend from Milepost 44 to Milepost 45.6. The total test section is 5.7 km long. Installations took place in the driving lane only during the week of October 3, 2011. The pavement sections were originally constructed between 1958 and 1971. The sections were overlaid in 2009 with 25-mm-thick asphalt concrete. The sections consist of two 3.7 m wide lanes in each direction. The shoulder width is 3 m throughout the entire test sections. The test site consists of 19 sections. Five sealants were installed using various treatment methods. Transverse reflective cracks were the main cracking type with a few longitudinal cracks developing in some sections.

New York Test Site

The New York test site is located on Chaplin Road (Road 21) in the Canandaigua area, southeast of Rochester. The test sections are located in the south and northbound lanes of Chaplin Road. The sections in the southbound lane start at Milepost 3003 and end at Milepost 3025. The test sections in the northbound lane extend from Milepost 3025 to Milepost 3003. The total test section length is 7.1 km. The section was milled and overlaid in 2010. It consists of one lane in each direction, and the lane width is 3.7 m. The shoulder width is 1.8 m throughout the entire test section. Sealant installation took place during the week of September 11, 2012. The test site consists of 13 sections. Six sealants were installed using various treatment methods. Transverse cracks were the main cracking type at the site with a few longitudinal cracks.

Virginia Test Site

The Virginia test site is located on Route 11 Northbound at Milepost 7.51 to Milepost 9.04. The section is 2.5 km long running from 1 km N NINT road. The section consists of two 3.7 m wide lanes in each direction. Sealant installation took place during the week of September 29, 2014. The test site consists of five sections. Four sealants were installed using a typical rout and seal (25 mm x 25 mm) and clean and seal treatments. Similar to the other test sites, transverse cracks were the main cracking type at the site with a few longitudinal cracks.

Michigan Test Site

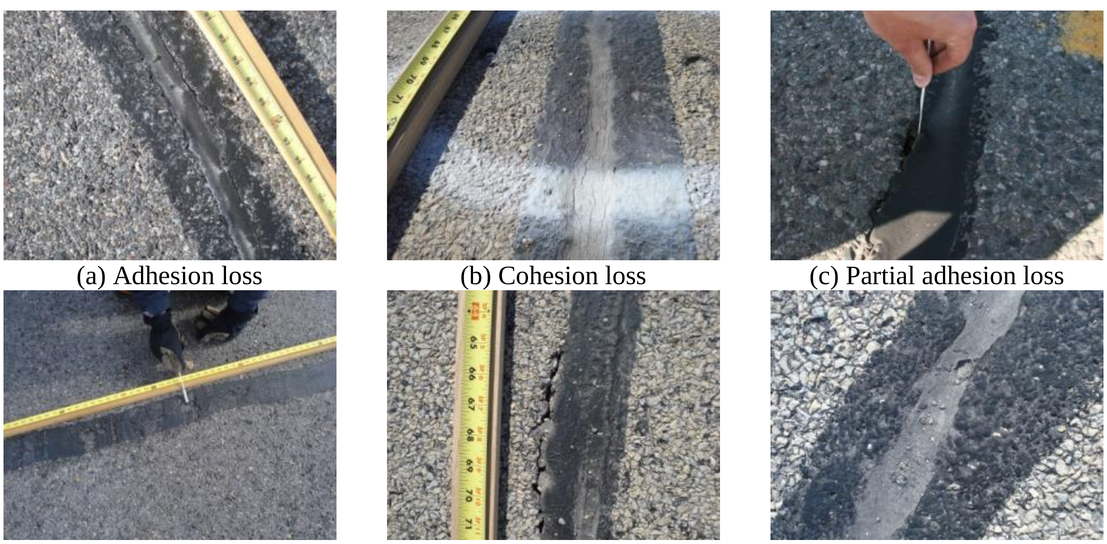
The Michigan test site was used for evaluating the performance of clean and seal treatment. The test site was installed and monitored by Michigan DOT. Sixteen hot-pour sealants covering a wide spectrum of products were installed in the field to accomplish the study objectives. The materials were mostly different from those used in the other test sites and were designed, installed, and monitored by the research team. However, since materials were collected at the time of installation and performance data were available, it was decided to add the test site to the test matrix.

The Michigan test site is located on the north and south bound lanes of US 127. The test sections are located between the south Roscommon County line and Canoe Camp Road. The total length of the section is 4.8 km. The test sections exist in the driving and passing lanes. Cracks in this section were treated using the clean and seal technique without routing.

Crack Sealant Field Performance

Distress Assessment

The field performance of sealants was evaluated by conducting a detailed field survey of crack sealants in accordance with AASHTO National Transportation Product Evaluation Program (NTPEP) protocols (NTPEP Report 16002.3). Field inspection was conducted annually during the project duration, immediately after crack sealant installation and every winter season from February to March. Performance data were routinely collected, including visual distress identification, crack displacement, temperature measurements, and material sampling for laboratory evaluation. This report summarizes the results obtained from the test section survey since 2011. The sealants were also visually inspected for material failure, loss in bond, and failure within the pavement. Figure 4 shows the common types of failure observed during the service life of sealants. Table 5 lists the distresses considered in the performance monitoring process. Pavement failure, identified as spalling in the routed cracks and hairline cracking developing near any of the cracks, was recorded separately.



(a) Adhesion loss (b) Cohesion loss (c) Partial adhesion loss
(d) Overband wear (e) Spalling (f) Stone intrusion

Figure 4. Commonly Observed Crack Sealant Distresses

Table 5. Distress Types Considered in the Field Evaluation

	Distress Type
Sealant material failure	Adhesion loss
	Cohesion loss
	Partial adhesion and cohesion loss
	Overband wear
	Tracking
	Stone intrusion
Pavement failure	Spalling
	Hairline cracking

During each field survey, more than 200 cracks were evaluated and crack conditions were digitally documented. Specifically, each crack was quantitatively evaluated for percent length of full-depth adhesive/cohesive failure, percent length of partial-depth adhesive/cohesive failure, percent length of overband wear, percent length of spalling failure, and the amount of stone intrusion.

A weighted rating system known as the performance index (PI) was implemented to develop a sealant damage index (Equation 1). Earlier studies (Masson et al., 1999; Smith and Romine, 1999; McGraw et al., 2007) were used as references to establish the rating system.

$$\boldsymbol{PI = 100 - (AC + PAC \times 0.5)} \tag{1}$$

where *AC* is the percentage of full adhesive and cohesive failures and *PAC* is the percentage of partial adhesive and cohesive failure.

Temperature and Displacement

During field installation, a wireless temperature node was installed at each test site to monitor the air temperature during the evaluation period. The ambient temperature data were used during test methods validation to find the critical temperature affecting sealants' performance. The temperature log obtained from the Minnesota test site in the year following installation is presented as an example in Figure 5. Based on the temperature log, the minimum temperature during the second year was -24°C on February 1, 2013, and lasted for 2 hr.

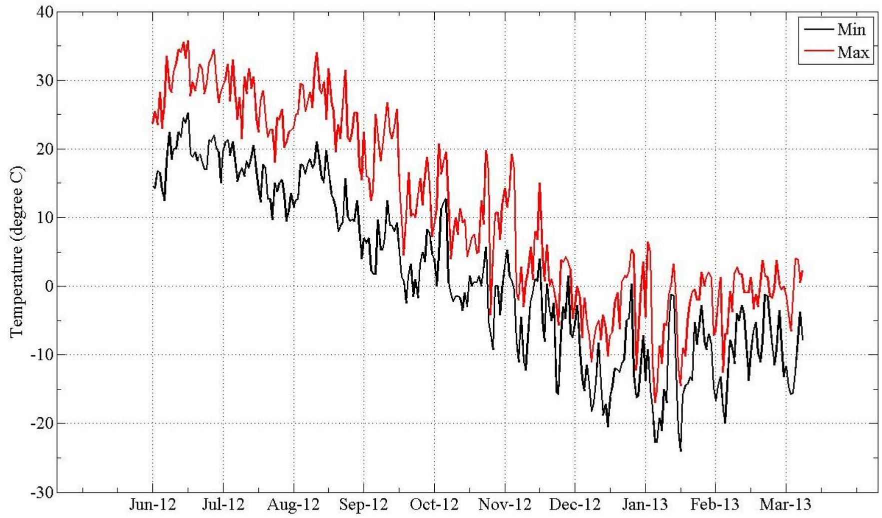


Figure 5. Ambient Temperature for Minnesota Test Site in the Year Following Installation

Effect of Treatment Type

To evaluate the effect of installation methods on sealant performance, cracks were treated by routing and sealing using different rout geometries and overbanding. Additionally, to evaluate the effect of the type of crack treatment, cracks of selected sections were cleaned and poured with sealant without any routing (uncut crack), referred to as clean and seal in this study.

Michigan Test Deck – A Case Study

Data Collection

The test deck installed by Michigan DOT prior to the start of the project was also added to the experimental program as a case study. The field performance at the Michigan test deck was evaluated by MDOT, also in accordance with NTPEP protocols. Field surveys were conducted twice every year (winter and summer) after clean and fill installation of hot-poured asphalt crack sealants. During each field survey, approximately 160 cracks were evaluated. Each crack was evaluated for percent length of cohesive failure and percent length of overband wear as plow abrasion.

Ambient air temperature was also monitored continuously. A data acquisition system was installed in the site to collect and store temperature data. Temperature data were downloaded to a laptop during the site visits and an accumulative variation of temperature was recorded. The main purpose of recording temperature readings was to investigate the effect of temperature on crack sealant cohesive performance and plow failure in the field and to study temperature performance ranges of the sealants.

Performance of Selected Sealants

The Michigan test bed was also evaluated using a rating system based on the same previous work supporting Equation 1, but emphasizing failure modes more relevant to the site.

Equations 2 and 3 also produce a separate PI (for each type of failure) that uniquely characterizes sealant condition for the Michigan case study.

$$\boldsymbol{PI = 100 - \%OBF} \quad (2)$$

$$\boldsymbol{PI = 100 - \%CF} \quad (3)$$

where *CF* is the percentage of cohesive failures and *OBF* is the percentage of overband failure caused by plow abrasion or sealant tracking. Unlike the NTPEP protocols, overband failure is added based on its significant effect on clean and fill treated cracks.

Field and Laboratory Aging of Sealants

One of the obstacles to developing a performance-based specification for asphalt crack sealants was the lack of a methodology for simulating short-term and long-term aging of the material. Therefore, procedures were developed to simulate different aging states. VOA method was used to simulate the aging and weathering of crack sealants during installation and service. In order to verify the effectiveness of the VOA method, several crack sealants aged in the laboratory were tested and compared with the test results obtained from field samples. A variation in test results between VOA laboratory-aged (LA) sealants and field-aged (FA) samples was observed and it was recommended that testing of field-aged sealant be conducted and results be evaluated in the context of the field survey data.

This section aims at evaluating and characterizing the effects of aging during installation and weathering on a sealant's critical rheological and mechanical properties, which can play a role in its performance. Therefore, in order to understand the true effects of aging on the properties of sealants, a wide array of crack sealants exposed to several aging protocols (Table 6) was studied and evaluated using laboratory tests developed as part of the performance-based specifications of hot-poured sealants (Ozer et al., 2015).

Aging Methods

Sealant test samples used in the experiments were prepared to represent various stages of aging that may occur over the lifetime of a sealant. Figure 6 illustrates the sample preparation pathways used in this study. Sealants are grouped into two categories: laboratory and field samples. Details of sample preparation at each aging stage are discussed in the next section. It should be mentioned that all aged samples prepared at each stage were obtained from the same sealant lot.

Note that aging estimates are made based on two low-temperature tests: crack sealant bending beam rheometer (CSBBR), and crack sealant adhesion test (CSAT). The test results obtained for the field-aged sealants (FA2 and FA3) are also compared with the results for lab-aged sealants.

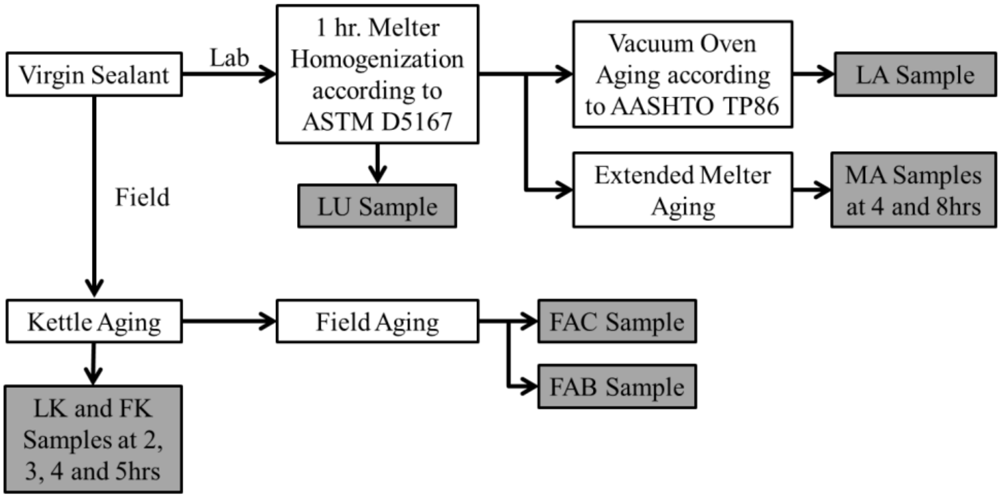


Figure 6. Sealant Sample Preparation Pathways to Represent Various Aging Stages of Sealants. Note: LU = Lab Unaged, LA = Lab Aged, MA = Melter Aged, LK = Lab Kettle aged, FK = Field Kettle aged, FAC = Crust portion of Field Aged, and FAB = Bottom portion of Field Aged

Table 6. Aging Procedures for Sealants Used in Performance Characterization

Aging Condition	Label	Remarks
Lab Unaged	LU	Lab homogenized sealants using ASTM D5167
Lab Aged	LA	Lab long-term aging using vacuum oven aging (AASHTO T 86)
Lab Kettle Aged	LK	Short-term kettle aging using a rental kettle
Field Kettle Aged	FK	Short-term kettle aging obtained from kettles during test site installations
Melter Aged	MA	Extensive aging time in the melter used to homogenize sealants
6-Month Field Aged	FA1	Field-aged samples collected during the first test site evaluation
1.5-Year Field Aged	FA2	Field-aged samples collected during the second test site evaluation
2.5-Year Field Aged	FA3	Field-aged samples collected during the third test site evaluation

Collection of Field-Aged Samples

During field installation, two to three samples were obtained from each material at different times. The first sample was collected right before installation, when the material was at the recommended temperature. The second and third samples were collected during installation. These samples were used to study the effect of kettle aging (short-term aging) on the rheological properties of crack sealants (Figure 7a). Also during the annual field surveys, field-aged (referred to as FA2 and FA3) samples were collected from the Minnesota, Wisconsin, Ontario, New Hampshire, and New York test sites during the second and third evaluation period (Figure 7b).

(a) Field kettle (FK) sampling

(b) Field-aged (FA) sampling

Figure 7. Collection of Field-Aged Samples

Laboratory Aging

The laboratory-aged samples were prepared first. The sealants were homogenized and melted for an hour in a lab melter according to ASTM D5167-13; these samples are considered laboratory-unaged samples. This is a standard procedure used in preparation of sealants for laboratory tests. The unaged sealants were then aged by a VOA procedure designed to simulate field aging of sealants. According to the procedure, 35g of sealant is kept at 115°C in the oven with vacuumed air for 16 hr (Figure 8). The last set of laboratory-aged samples was prepared using the melter by heating and stirring the sealants for another 4 and 8 hr to represent aging during the installation.

Figure 8. Vacuum Oven Aging to Simulate Long-Term Aging for Crack Sealants

Three different aging methods were practiced in the laboratory: extended melter aging (MA) according to ASTM D5167, kettle aging (LK) using a rental kettle, and VOA (LA) according to AASHTO T P86. To study the effect of these three aging methods, test results are expressed in terms of the Aging Index (AI) defined by relative change in rheological property of aged and unaged sealant.

$$Aging\ Index\ (AI) = \frac{S_{aged}}{S_{unaged}} \tag{4}$$

where S is the CSBBR stiffness at 240 sec of creep loading. AI higher than unity is an indication of increasing in low-temperature stiffness and AI lower than unity means that sealant is getting softer or degraded.

Laboratory Validation

Field performance data collected from the test sites were used in validation of the crack sealant grading test methods. Information collected from lab- and field-aged samples was used to establish correlation between laboratory and field performance and to validate the lab tests and fine-tune the thresholds (Figure 9). The thresholds were selected by comparing the lab parameters with field performance using an iterative approach that yielded consistent ranking and correlation between field and laboratory test results.

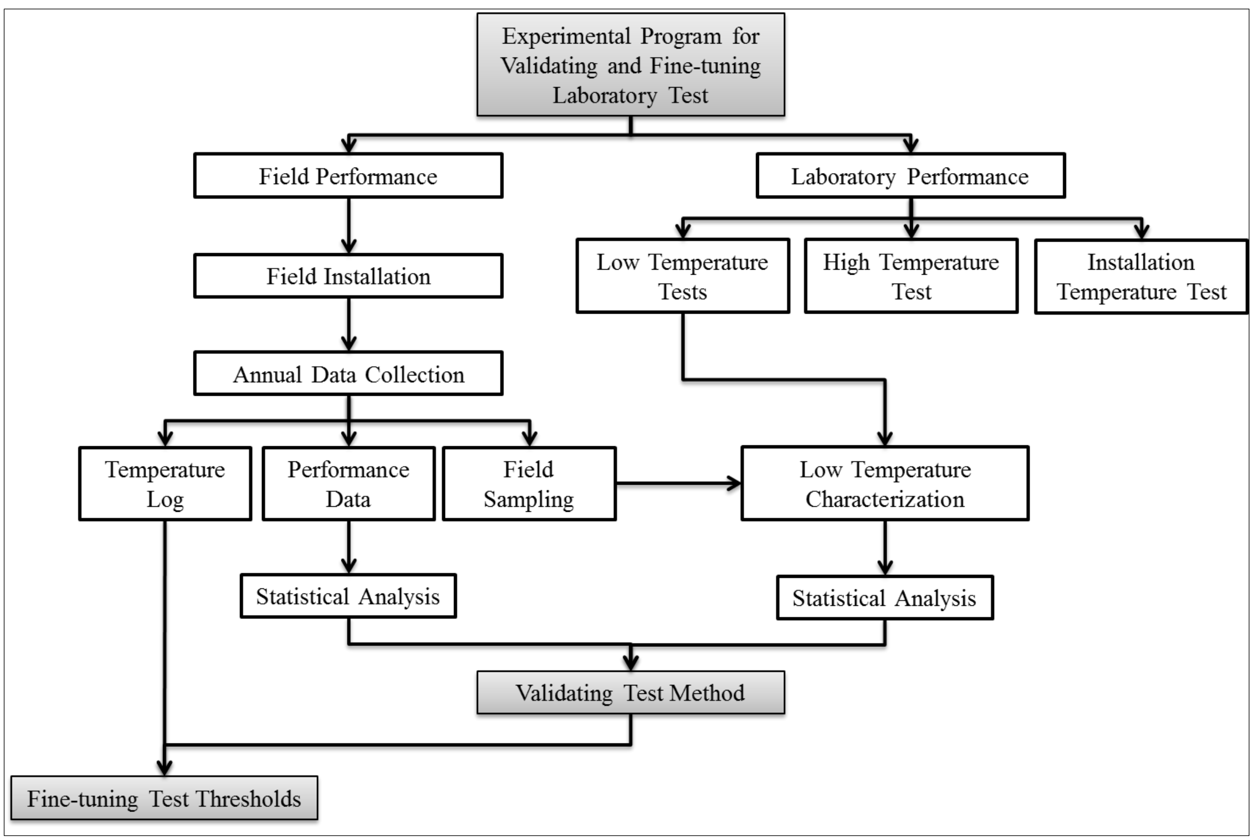


Figure 9. Experimental Program for Validating and Fine-Tuning Laboratory Test Method

High-Temperature Grading

Background

Tracking failure of sealants results from wearing of the material subjected to the shear loading applied by vehicles. The main cause of this failure can be improper selection of sealant type, early traffic opening, or high temperatures. In the performance grading system, tests that predict tracking failure are also used to determine the high-temperature grade. In Phase I of the crack sealant study, the multiple stress creep recovery (MSCR) test was developed using a dynamic shear rheometer (DSR) to determine high-temperature grading and tracking resistance.

The MSCR test is a well-developed procedure to determine permanent deformation characteristics of asphalt materials. Testing protocol includes multiple cycles of creep and recovery resulting in a model describing Non-Newtonian viscous properties indicating shear resistance of the material. The coefficients C-value (flow coefficient) and P-value (thinning coefficient) describe the Ostwald model parameters also used in defining the performance threshold. Performance correlation and thresholds were determined in the previous phase using another laboratory-scale torture test (Al-Qadi et al., 2009). The MSCR test has yet to be validated using field performance data.

Since the MSCR test procedures are complex and time consuming, an alternative and more practical test was sought in this phase to fulfill the same performance grading requirements as the MSCR. The alternative high-temperature grading test is presented in this section, for high-temperature grading of hot-poured crack sealants. This test also simulates tracking failure of sealant due to shearing at high temperatures using a practical and less time consuming testing protocol. Some of the major attributes of this test are explained as follows:

- DSR equipment is used for testing.
- Shear strain is increased at a constant rate until complete failure to observe yield point for sealants (shear strains goes up to 600%).
- A shear rate of 0.01 sec^{-1} was selected.
- Test temperatures ranged from 46 to 82°C with 6°C increments.
- A threshold value was determined as a cut-off value for high-temperature grading. The threshold value was initially determined based on MSCR results. The test proposes a threshold shear stress or resistance at high temperatures above which acceptable tracking resistance should be expected.

General Test Sites

The testing protocol for predicting tracking failure was applied to ten selected sealants for grading and evaluation. The specimens were prepared according to ASTM D5167 (1 hr melting and homogenization at recommended installation temperature). Unaged samples were selected to find the high-temperature grade.

Michigan Test Deck

Six out of sixteen sealants that were installed and evaluated by MDOT were selected to correlate field and laboratory performance. The main difference between Michigan test site evaluations and other test sites evaluations is the frequency of field surveys, which were conducted twice a year (winter and summer) as compared to once in other test sites (after winter). This helped evaluate the overband failure separately for hot and cold seasons and correlate it with corresponding laboratory performance.

Viscosity

Viscosity plays an essential role in predicting the field performance of hot-poured crack sealants: upper and lower viscosity limits must be identified. The upper limit ensures that the material is sufficiently liquid so it can be poured; the lower limit helps avoid excessively fluid sealants, which create problems in filling cracks during installation (Al-Qadi et al., 2009). A Brookfield rotational viscometer was used to measure the apparent viscosity of hot-poured crack sealants that simulates installation conditions (AASHTO TP 85).

Low-Temperature Grading

Crack Sealant Bending Beam Rheometer

The CSBBR test, a modified Bending Beam Rheometer (BBR) test, was introduced to measure the flexural creep of crack sealants at temperatures as low as -40°C. This procedure has been adopted as an AASHTO TP 87 provisional standard. Two performance parameters were suggested for use in the specification: stiffness at 240 sec (S240), and average creep rate. The field-aged samples were tested at three different temperatures for better characterization of sealant performance. A stiffness master curve was obtained for each sealant at a reference temperature.

Sealants with similar field performance, according to their PIs, were grouped together based on statistical testing. The sealants were evaluated based on their respective test results and grouped based on statistical tests. Groups with matching lab and field performance indicated that the laboratory test parameter provided positive correlation to field performance. Two separate statistical methods were used to determine groupings for the data collected from the lab and field. Field data were statistically analyzed using the Games-Howell test and categorized in different subsets. Each subset presents a group of sealants with a similar field performance. Another statistical test was also applied to the test parameters obtained from the CSBBR test. Because of the normal distribution of laboratory test results, the Tukey test was used to categorize sealants in different subsets. The subsets of field and lab data were compared separately for each test site.

Crack Sealant Direct Tension Test

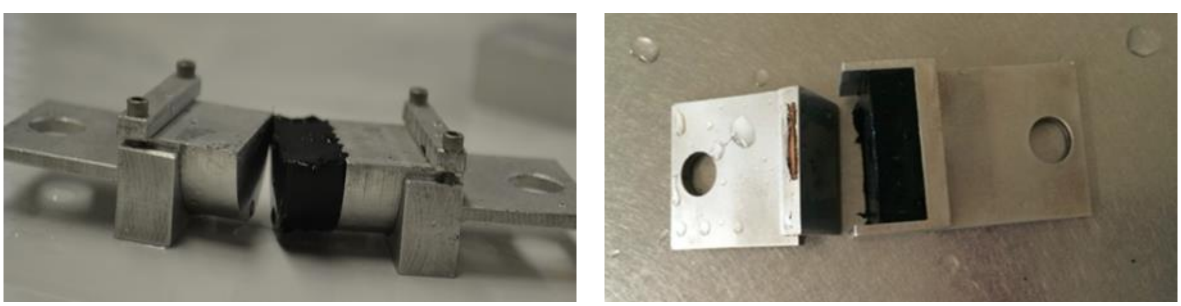
The Crack Sealant Direct Tension Test (CSDTT) has been adopted as an AASHTO provisional standard (AASHTO TP 88). Extendibility at the test temperature is suggested as a performance parameter. Similar to the CSBBR test method, sealants with distinct lab results were expected to be grouped in the same field performance subsets to validate the CSDTT test method.

Modified Adhesion Test

Field-aged samples were tested using the AASHTO provisional standard TP 89 CSAT to seek correlation to field performance (Figure 10a). A similar approach used for CSBBR was followed to interpret the test results. Field and laboratory test data were analyzed using independent statistical tests, and similarly performing sealants were grouped together. The subsets of field and lab data were compared separately for each test site. Overall, no specific trends were obtained for the effect of test temperature. None of the sealants in this site passed the criterion for adhesion load (50 N). Sealants performed differently depending on the tested temperature. Some of the critical observations regarding this test are summarized as follows:

- Repeatability of test results was poor. The field-aged specimens showed a high coefficient of variation (CoV) - CoV of the loads could reach as high as 62%. Variability was higher with the energy results.
- The test was not able to discriminate sealant adhesion performance. No significant differences were observed among the adhesive capacity of different sealants.
- Sample preparation and the quality of the shim used to create the notch are key factors affecting the quality of test results.

Therefore, a more robust and repeatable adhesion test addressing the abovementioned challenges were sought through modification of CSAT. Different test trials were introduced by changing the fixture geometry used in the DTT machine. A larger cross-section was used to provide a larger contact area. Rectangular cross-sections of 30 mm x 20 mm were then introduced (Figure 10b). A 6 mm notch from each side of the interface was applied using the mold release. The modified adhesion test mold assembly consists mainly of two T-shape end pieces and a U-shape to confine the end pieces. The reason for using a U-shape end piece is to get a good grip of the mold assembly. The notch would minimize bulk sealant deformations and redirect the applied energy for interface debonding. The end tab contact surface is 30 mm × 20 mm. Tests were conducted with four replicates at selected temperatures. This set up was identified as the main adhesion test and used to test all sealants after preliminary evaluation was performed.



(a) CSAT **(b) Modified Adhesion Test**

Figure 10. Specimen Configuration for Current and Modified Tensile Adhesion Tests

Test molds were made from 6061 type aluminum. The adhesion interface was polished to No. 32 grit. The molds consist of three parts: two end tabs, and one U-shape. The notch area is applied to produce a symmetrical interface. The U-shape part can be used to create the notch area by first marking the location where the notch is introduced. The process is repeated for the other side notch. The proposed design of the molds provides a very easy demolding process. It also minimizes the impact of the specimen weight during the conditioning. The symmetry and ease of handling provided by this design improved the results significantly.

After a preliminary evaluation of the new and improved adhesion test method, a set of evaluation criteria was established to verify the robustness of the new test and determine whether it could fulfill the objectives of the study. Evaluation criteria were as follows:

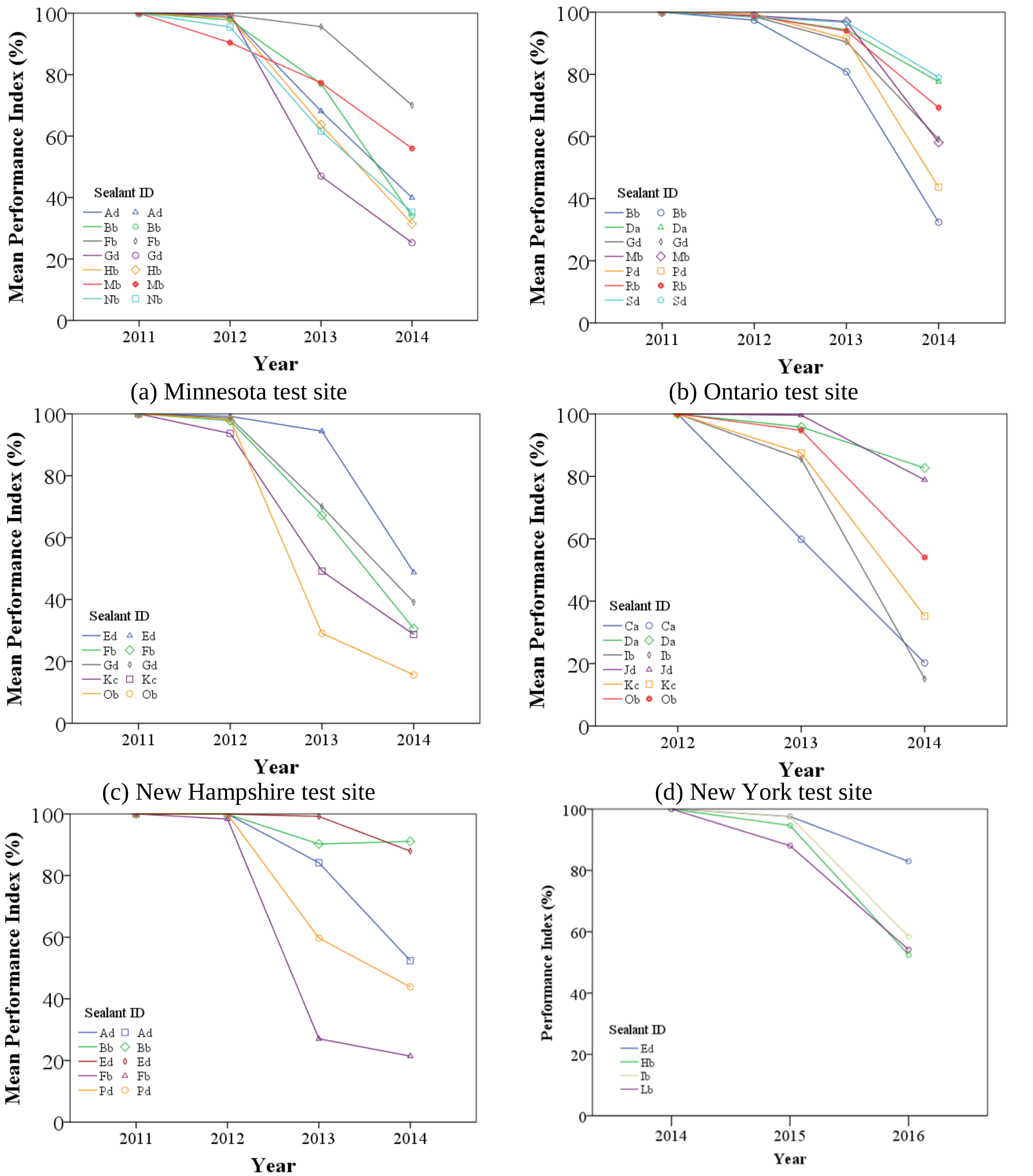
- Repeatability between test replicates and users
- Meaningfulness of results (i.e., whether the results follow a trend with temperature and aging)
- Discrimination potential among sealants to determine a pass/fail threshold

RESULTS

Field Performance Review

General Condition Summary

A summary of evaluation results (using PI) at different test sites is presented in Figure 11 for rout and seal sections and Figure 12 for clean and seal sections. Overall, severe changes were noticed in the failure extent between winter 2013 and winter 2014. Adhesion loss, which allows the penetration of water into pavement layers, was the most observed sealant failure in the field. The amount of adhesion loss is calculated based on the effective length of the crack, which is the total length of spalling along the crack subtracted from total crack length. Figure 11 shows the significant drop in PI values for the majority of sealants after the second and third winters. Severe failure of the clean and seal sections was also observed after the first and second winters (Figure 12).



(a) Minnesota test site

(b) Ontario test site

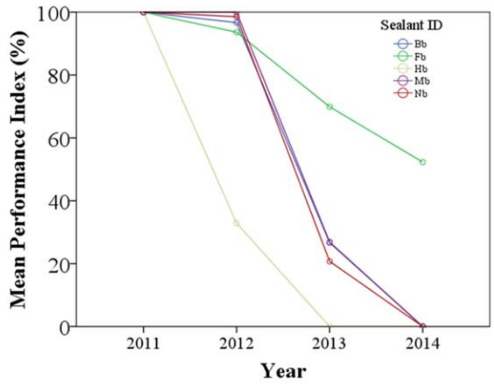
(c) New Hampshire test site

(d) New York test site

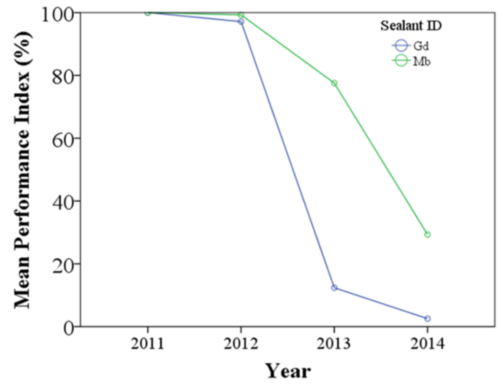
(e) Wisconsin test site

(f) Virginia Test Site

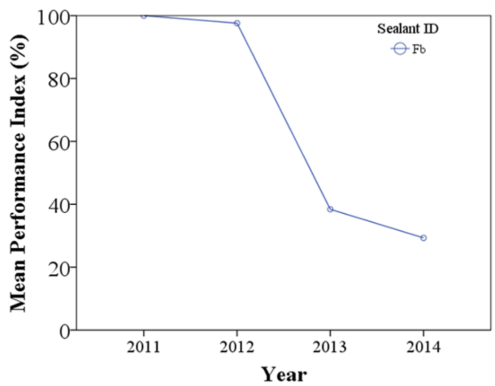
Figure 11. Overall Performance of Sealants for Rout and Seal Sections in Different Test Sites



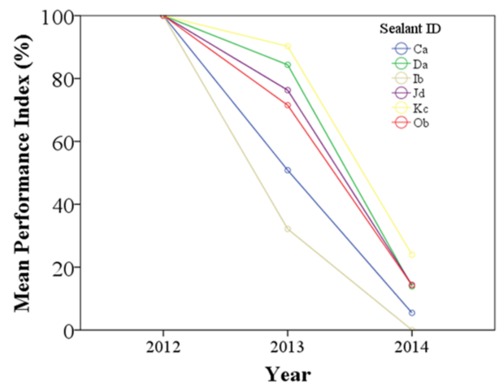
(a) Minnesota test site



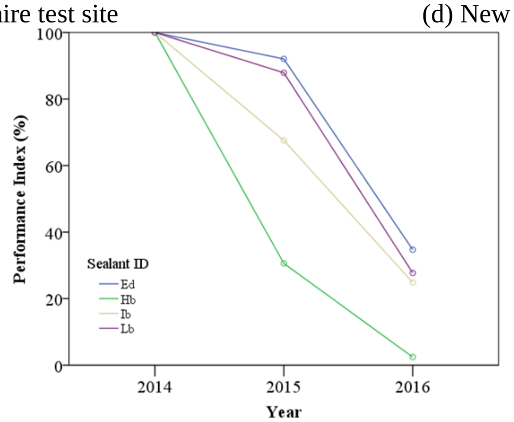
(b) Ontario test site



(c) New Hampshire test site



(d) New York test site



(e) Virginia Test Site

Figure 12. Overall Performance of Sealants for Clean and Seal Sections in Different Test Sites

Temperature and Displacement

The detailed temperature log for the five coldest days at four test sites is presented in Table 7. The corresponding crack displacements for each winter at each site are shown in Figure 13.

Table 7. Summary of Minimum Temperatures for the Five Coldest Days at All Test Sites

Test Site	Temperature (°C)					
	1	2	3	4	5	Average
Minnesota	-24.0	-22.8	-22.8	-21.0	-20.5	-22.2
Ontario	-33.2	-29.0	-28.8	-27.5	-27.5	-29.2
New York	-21.7	-20.7	-20.5	-19.7	-19.0	-20.3
New Hampshire	-26.7	-24.0	-23.5	-22.8	-22.2	-23.8

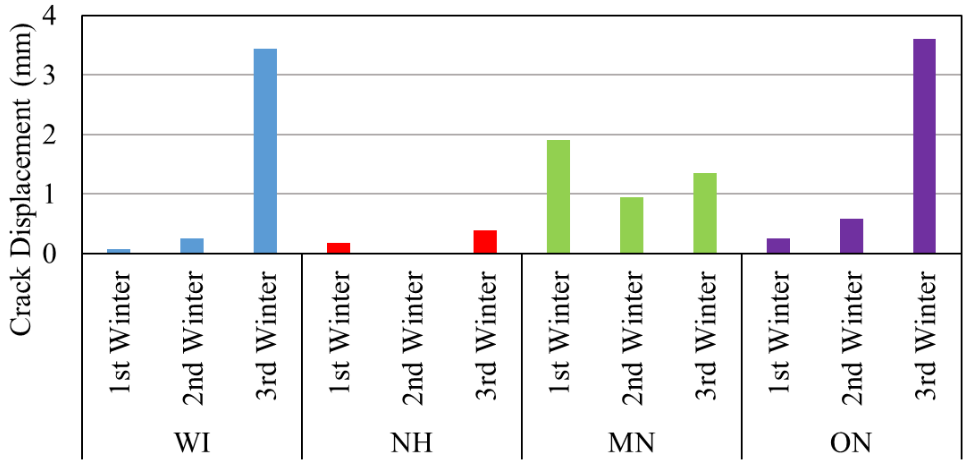


Figure 13. Average Crack Displacements Measured at Each Test Site

Effect of Treatment Type

The effect of different treatment methods on the performance of crack sealants is compared in Figure 14. Following the second winter at all test sites, there was a significant drop in the PI for clean and seal sections. The difference between clean and seal sections and rout and seal sections was approximately 30% on average. After winter 2014, almost all clean and seal sections had failed.

Overband application was also evaluated as another factor that affects the performance of crack sealants. The effect of overbanding is evident in Figure 15. Foregoing an overband as a test variable in some of the sections in the New York test site led to a significant drop in the performance of sealants. The average of differences between the sealants with overband and without overband after both winters is about 18% to 20%. Similar observations were reported in SHRP project H-106 (Smith and Romine, 1999).

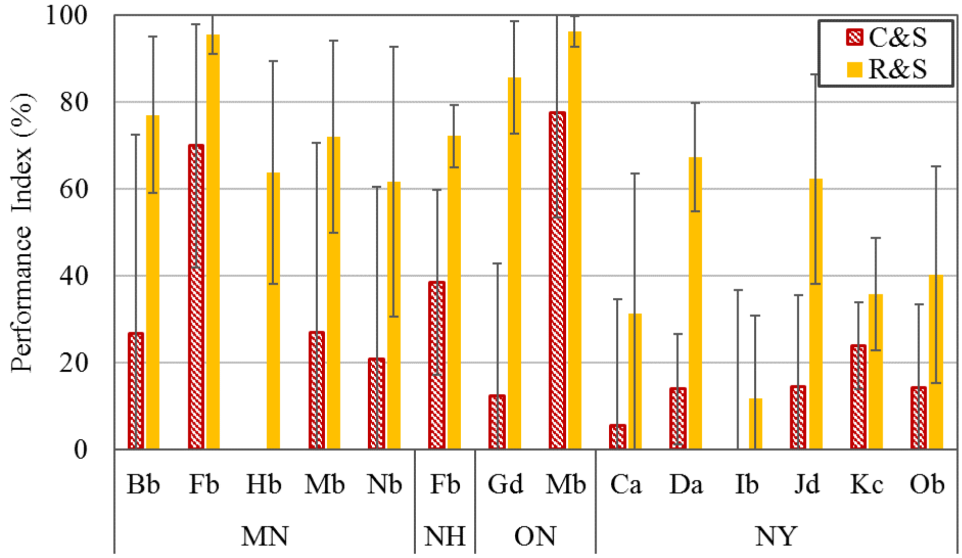


Figure 14. Effect of Treatment Type on Crack Sealants Performance after Second Winter for Different Materials at Different Test Sites. Note: C & S = Clean and Seal; R & S = Rout and Seal

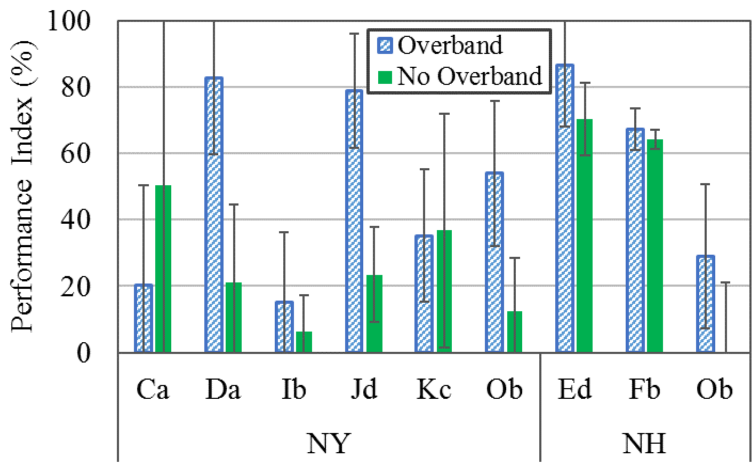
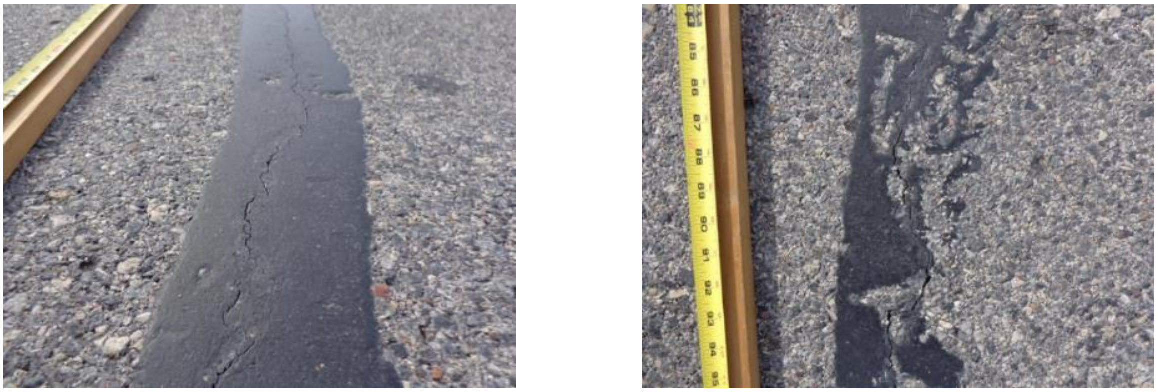


Figure 15. Effect of Overband Application on Crack Sealants Performance for Different Materials at Different Test Sites after Second Winter

Michigan Case Study

This section summarizes the field performance reviews from the Michigan test deck since 2011. The common crack filling (clean and seal) failures as observed from the site were cohesive failures resulting from crack movements and overband failure due to tire tracking and plows (Figure 16). Sample pictures from sealant field performance are presented in Figure 17. The sealant in crack 1.1 failed due to poor cohesive performance while the overband was still in contact; the sealant in cracks 14.9 and 16.6 failed due to poor cohesive and overband performance, respectively.



(a) Cohesive failure (b) Overband failure

Figure 16. Common Failure Modes of Clean and Seal Treatment

(a) Crack 5.7 (b) Crack 9.8 (c) Crack 8.7 (d) Crack 1.1 (e) Crack 14.9 (f) Crack 16.6

Figure 17. Sample Pictures for Sealants Field Performance in Michigan Test Site

Six crack sealants with consistent installation conditions were selected from the Michigan deck - Sections 03, 04, 06, 07, 12, and 16. The corresponding ASTM D6690 classification of each sealant is provided in Table 8. Out of six hot-poured crack sealants selected in this study, three are Type I (Sections 04, 06, and 07), one is Type II (Section 16), and two are Type IV (Sections 03 and 12). The sealants were classified based on effectiveness of the seal with respect to climatic conditions, low-temperature performance, and the percentage of extension. Based on the field performance and as a result of resistance against plows, sealants at Sections 04 and 12 reflected good field performance, Sections 07 and 16 demonstrated fair performance, and Sections 03 and 06 had poor performance. Because of their cohesive properties, sealants at Sections 03, 04, and 06 had very good or good performance, while sealants at Sections 07, 12, and 16 showed fair or poor performance.

Table 8. ASTM Specification for the Selected Crack Sealants

Section (ID)	ASTM D6690 Type	Installation Temperature (°C)	Melting Time (Min)	Field Performance	
				Plow Abrasion	Cohesive
03	IV	193	50	poor	good
04	I	193	45	good	good
06	I	193	45	poor	very good
07	I	193	45	fair	poor
12	IV	193	50	good	poor
16	II	193	45	fair	fair

The overband failure of sealants in winter can be attributed to plow abrasion although it may also happen due to insufficient tracking resistance during summer period where sealant deformations can be high. In hot seasons, the shear strength and stiffness of sealants can be reduced significantly, so they may be picked up or tracked by the vehicles. The PI based on plow abrasion of six sealants for the initial 3 years of field performance is shown in Figure 18. A gradual reduction in the PI value from 2011 to 2012 was observed for all sealants. It can be seen that the sealant at Section 12 shows the least amount of changes in the PI value, while the sealant at Section 3 shows complete overband failure.

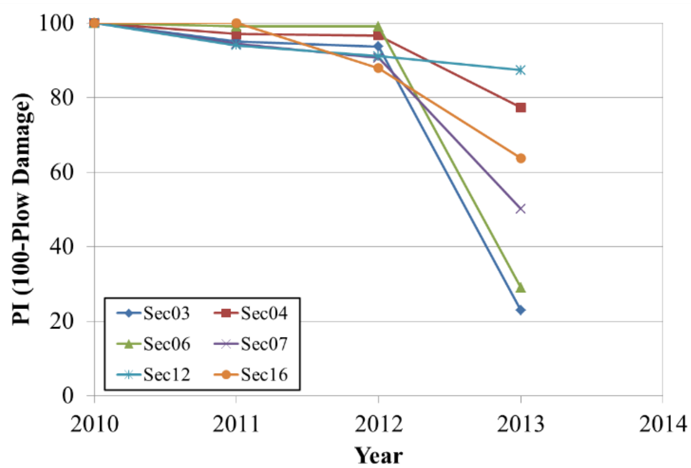


Figure 18. PI of Selected Sealants Based on Plow Abrasion (%OBF: Overband Failure)

Similar to plow damage analysis, the PI of the six sealants was calculated during the 3 years of service life based on cohesive failure, as shown in Figure 19. A reduction in PI was observed with the passage of time. All sealants showed a PI value higher than 50% by the end of 2013 (3 years of service life). However, a significant reduction in the PI value could be observed from 2012 to 2013. Sealants at Sections 12 and 6 showed relatively maximum and minimum reductions in PI value, respectively. Sealants at Sections 3 and 4 paralleled the deterioration trends of Sections 7 and 16 with a slightly better starting condition after year 2.

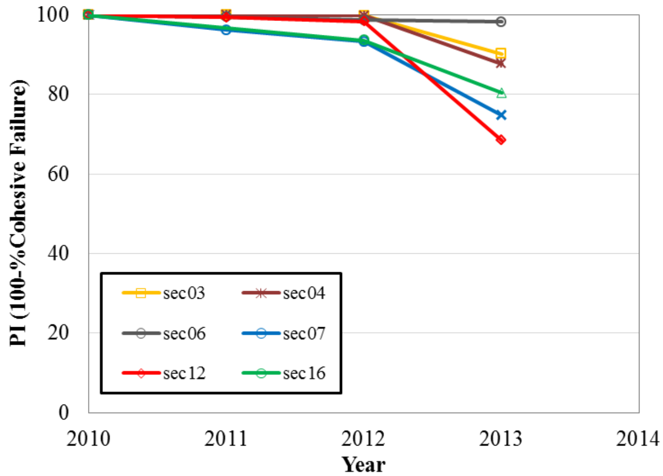


Figure 19. Performance Index of Selected Sealants Based on Cohesive Failure

During the seasonal surveys, the average crack displacement readings were obtained for specific sections to ascertain the effect of temperature on crack displacement and crack spacing. Average crack spacing and the net movement of 10 consecutive cracks per section were measured and recorded. Figure 20 presents the average crack displacment (bars) and spacing (line) from the field measurments during the winter surveys for the selected sections.

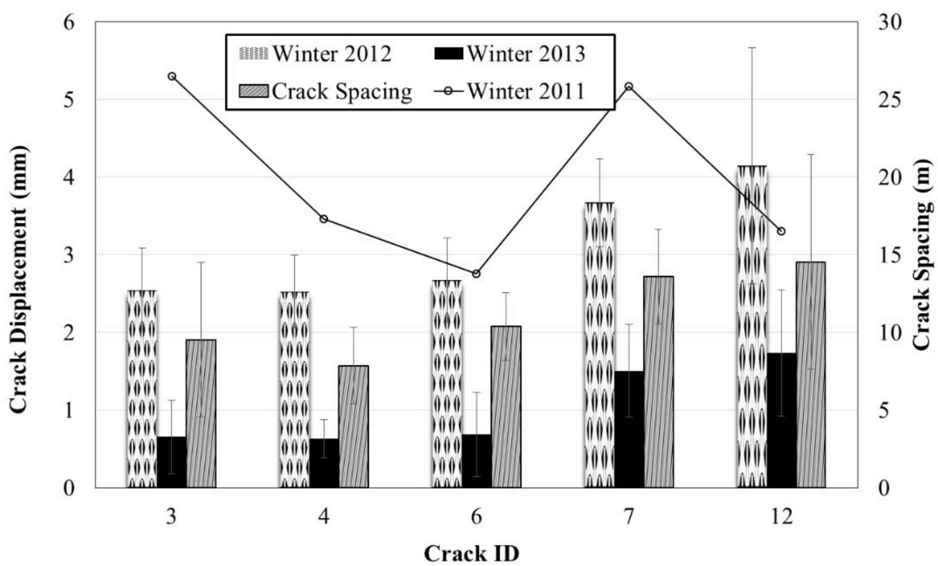


Figure 20. Average Crack Displacement and Spacing

It may be noted from Figure 20 that crack displacement during the winter of 2012 was lower than that of winter 2011. This may be atrributed to the fact that the temperature was relatively lower in winter 2011 than winter 2012. Data were unavailable for the sealant at Section 16.

Aging of Sealants

Evaluation

The aging method developed to simulate long-term sealant aging in the laboratory is VOA according to AASHTO TP 86. Laboratory aging (LA) results for CSBBR stiffness are presented in Figure 21 The results show that, except for sealant Ob, all sealants become stiffer. However, the increments in the Aging Index (AI) for the sealants are not the same. This can be related to the sealant's aging potential, which is discussed later. VOA may increase the stiffness (AI higher than 1 for CSBBR stiffness); however, the aging effect has a minimal effect on maximum adhesion load of the aged samples tested by CSAT (Figure 22). For most sealants, the AI is almost unity at temperatures close to their grades, which indicates that adhesion load does not change during the aging process.

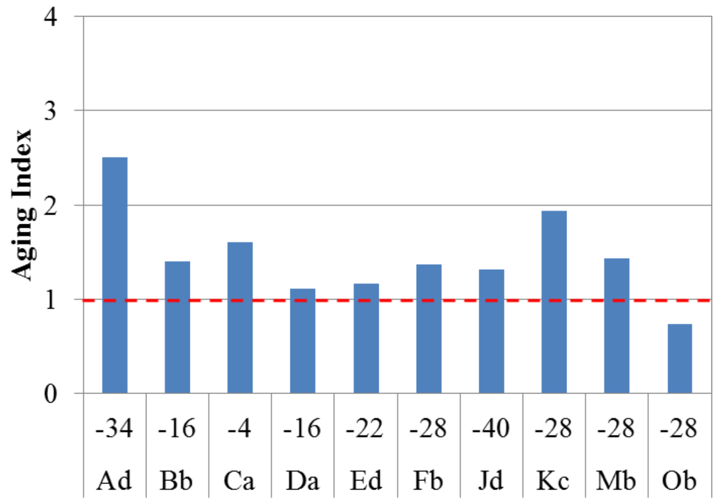


Figure 21. Aging Index (AI) for Different Laboratory Aging Methods Based on CSBBR Stiffness at 240 sec

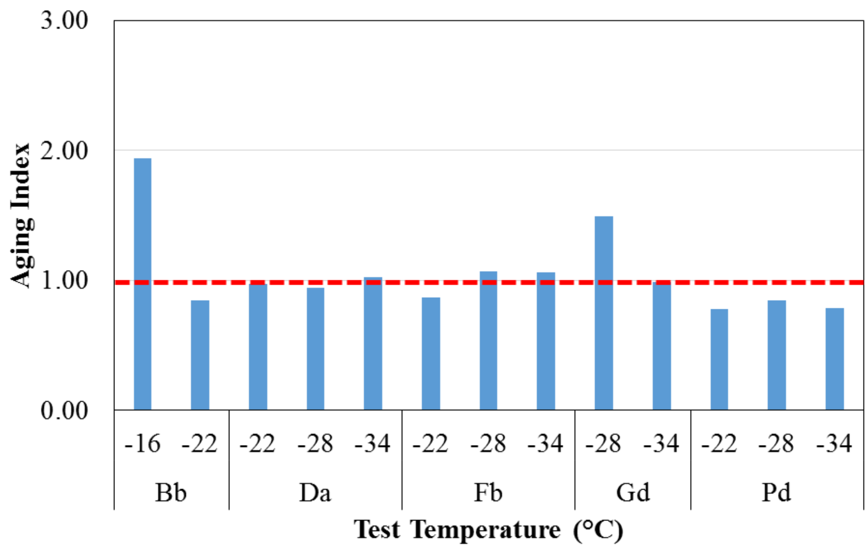


Figure 22. Aging Index for Vacuum Oven Aging (VOA) Methods Based on Maximum Adhesion Load

Validation

CSBBR test results on different aged samples are compared in this section. The information collected from lab- and field-aged samples is used to establish any possible correlation between laboratory and field aging. Low-temperature stiffness and average creep ratio (ACR) at 240 sec at different aging conditions, lab-aged (LA) and field-aged samples collected after the second and third winter (FA2 and FA3), are compared in Figure 23 for sealant Bb at three different temperatures. For most sealants, stiffness increases with field aging. Comparison of FAs with LA samples is further investigated in the following sections.

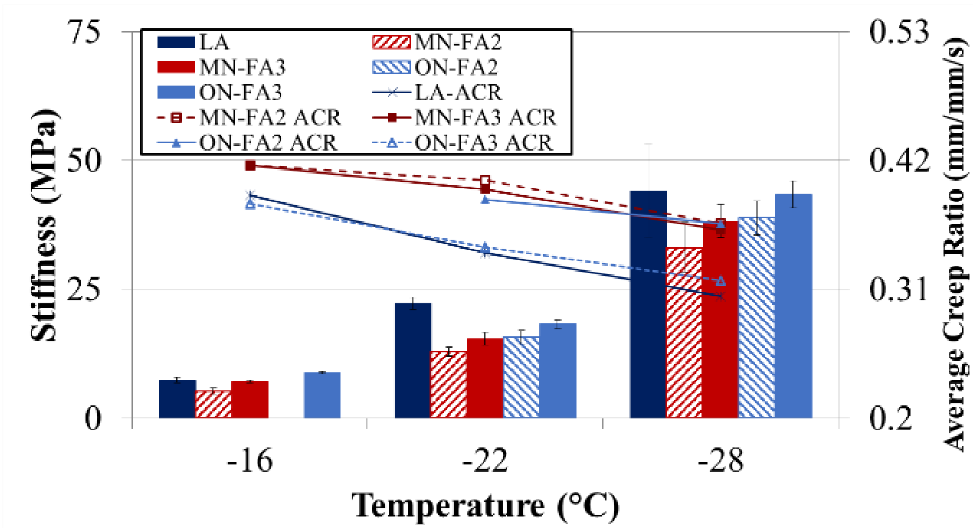


Figure 23. CSBBR Stiffness and Average Creep Ratio (ACR) at 240 sec at Different Aging Conditions Tested at Three Different Temperatures for Sealant Bb

For a better comparison between laboratory aging and field aging, the stiffness master curves obtained from the test data at three different temperatures, are used instead of the single stiffness value at 240 sec. Overall, two different trends can be seen for different sealants:

- Sealants becoming stiffer following laboratory aging (VOA) compared with real field-aged samples, such as sealant Da in Figure 24 (VOA could be over-aging the sealants)
- Sealant being stiffer during field aging compared with laboratory aging, such as sealant Ad in Figure 25 (VOA could be under-aging the sealants)

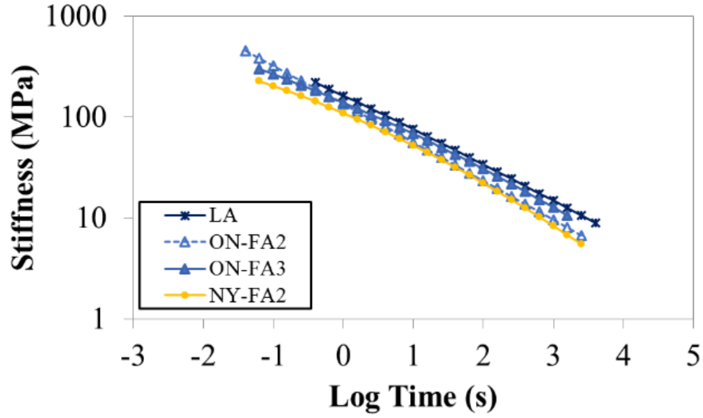


Figure 24. CSBBR Stiffness Master Curves Comparing Laboratory-Aged (LA) with Field-Aged (FAs) Samples for Sealant Da

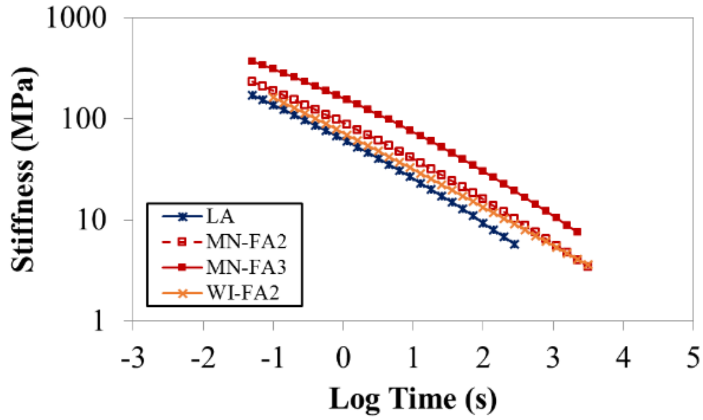


Figure 25. CSBBR Stiffness Master Curves Comparing Laboratory-Aged (LA) with Field-Aged (FAs) Samples for Sealant Ad

To summarize the comparison between field-aged and lab-aged sealants based on the stiffness master curves presented in Figure 24 and Figure 25, the average difference between the curves was calculated as a percentage:

$$S_{dif} = \left(\sum_{i=1}^{n} \frac{(S_i^{LA} - S_i^{FA})}{S_i^{LA}}\right) \Big/ n \times 100 \quad (5)$$

where

S_i^{LA} = Stiffness at a specific creep loading time for laboratory-aged sample
S_i^{FA} = Stiffness at a specific creep loading time for field-aged sample
n = Number of data points

The average difference in stiffness between field-aged samples and lab-aged sample is summarized in Table 9. This table illustrates the potential of lab aging procedure for representing field aging calculated from the tests conducted on field-aged samples. This is a negative gap between stiffness values obtained using lab-aged procedure and field-aged sealants.

The cells shaded with green are the ones with stiffness differences within ±10%, or LA stiffness higher than field-aged samples, which are considered acceptable because it is conservative to overestimate stiffness. The range of gap varies between approximately ±30% of field-aged stiffness; with the majority of samples ranging within the ±10% difference band. There are some sealants for which aging properties are underestimated by lab aging compared to the field aging. These are the type of sealants one may consider changing the severity of aging protocol to accelerate aging in the lab. On the other hand, lab aging overestimated the stiffness of several other sealants. This is considered a conservative approach since those sealants will experience more aging after the end of 3-year monitoring period. Therefore, having lab-aged sealants stiffer than field-aged sealants is considered a conservative approach. Based on the number of acceptable cases, the VOA procedure was able to satisfactorily represent field aging at a rate higher than 70% of the cases.

The differences can be attributed to several factors. First, the samples collected from the routs are homogenized in the lab, thus resulting in blended properties of sealants. It is shown that field aging has a gradient starting from the surface. The properties of the bottom portion of the sealant may remain unchanged or weakened due to moisture infiltration. Second, field samples were collected from sites that were a maximum of 2.5 years old. As the materials continue to be aged in the field, these properties may continue to change. Third, deicing chemicals and salts may be another factor affecting the stiffness and adhesion properties in addition to aging, which cannot be covered by the laboratory tests. Therefore, it should not be expected to obtain one to one match between field and lab aged test results as there are various factors that cannot be simulated in the lab. However, when the stiffness master curves obtained from CSBBR test for field-aged samples and laboratory-aged samples are compared, it was determined that VOA is a reasonable aging method for simulating 2 to 5 years of field aging.

Table 9. Comparison between Field-aged and Lab-aged Sealants based on Stiffness Master Curves Illustrating the Change in their Stiffness as Compared to Lab-aged Stiffness

Sealant	Test Sites						
	Minnesota		Ontario		Wisconsin	New York	New Hampshire
	2nd yr.	3rd yr.	2nd yr.	3rd yr.	2nd yr.	2nd yr.	3rd yr.
Ad	-13.10%	-32%	-	-	-6.80%	-	-
Bb	5.90%	2.00%	1.60%	0.20%	27.40%	-	-
Ca	-	-	-	-	-	6.50%	-
Da	-	-	8.90%	3.30%	-	11.80%	-
Ed	-	-	-	-	11.30%	-	-16.60%
Fb	-14.00%	-3.80%	-	-	0.10%	-	-2.70%
Gd	-1.50%	2.70%	1.60%	-9.00%	-	-	-7.10%
Hb	3.40%	0.20%	-	-	-	-	-
Mb	-2.70%	6.10%	3.20%	3.00%	-	-	-
Nb	-32.50%	-17.30%	-	-	-	-	-
Ob	-	-	-	-	-	-45.20%	-13.00%
Pd	-	-	-2.70%	-6.20%	-11.80%	-	-
Sd	-	-	-10.50%	-12.50%	-	-	-

Validation of Laboratory Tests

This section summarizes the field performance and laboratory data results and presents the correlation between the sets of data using statistical methods.

Dynamic Shear Rheometer

Laboratory Results

The sealants selected for testing at high temperature are summarized in Table 10. According to the MSCR procedure, the sealant high-temperature grade was selected where C-value (flow coefficient) was higher than 4.0 kPa.s and P-value (thinning coefficient) was higher than 0.7. MSCR coefficients also show that the C-value is more critical for defining the high-temperature grade than the P-value.

Table 10. Summary of High-Temperature Grade for Selected Sealants Used in this Study

Sealant ID		MSCR Parameters		High-Temperature Sealant Grade (°C)
		C-value (kPa.s)	P-value	
Ad		4.4	0.91	70
Bb		4.8	0.92	64
Ca		4.6	0.96	70
Da		4.7	0.91	76
Ed		4.2	0.86	76
Gd		5.2	0.86	76
Jd		5.5	0.86	70
Ob		4.5	0.79	82
Pd[1]		NA	NA	64
Sd		6.3	0.85	76
MI[2]	3	4.8	0.92	64
	4	6.6	0.82	76
	6	7.9	0.91	70
	7	5.4	0.78	82
	12	6.6	0.90	70
	16	4.9	0.83	76

[1] The grade for sealant Pd is predicted based on coefficients at 70°C.
[2] Sealants from MI test site has identified by numbers and were used for field validation.

A typical result of the yield test conducted for sealant Ad at different temperatures is presented in Figure 26. The tests were conducted at three different temperatures initially based on the grade defined by the MSCR test. As temperature increases, the capacity of the material to sustain shear loads decreases. Since the sealants do not exhibit a clear yielding point or cannot be determined with only monotonic loading test, yield stress is selected as a threshold criterion at specific strain levels (50%, 100%, and 200%).

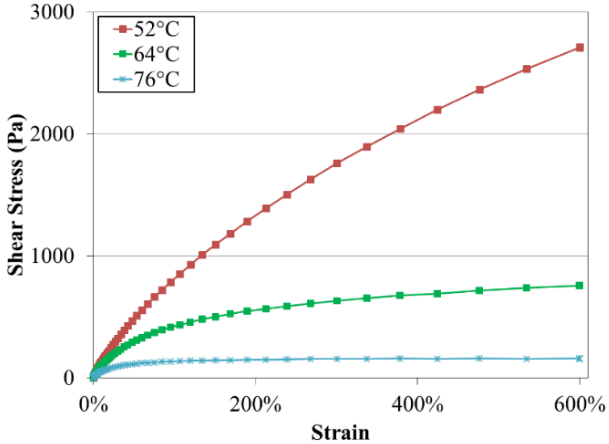
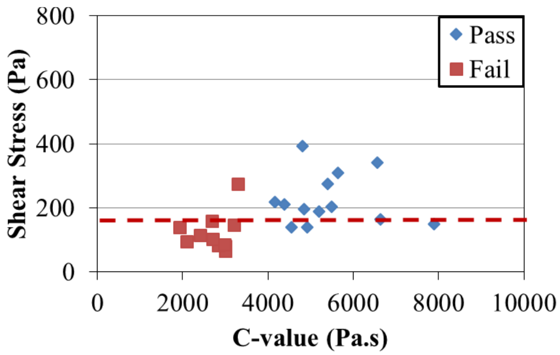
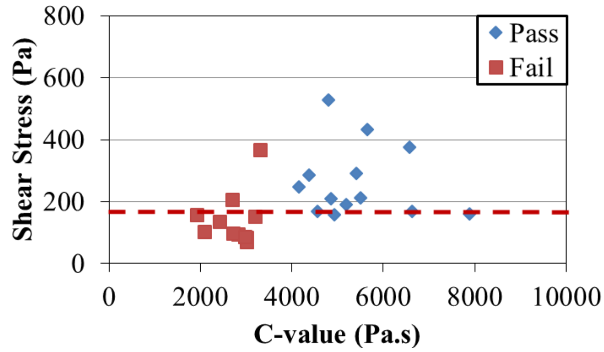


Figure 26. Shear Stress vs. Strain for Sealant Ad at Three Different Temperatures

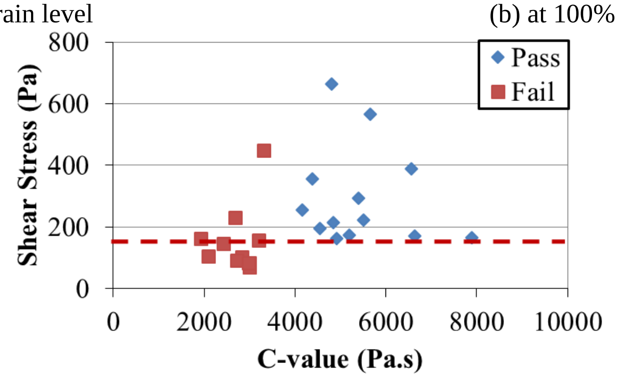
The two high-temperature grading methods are shown in Figure 27 by comparing the shear stress values from the yield test at three strain levels and C-value from the MSCR test. There is a reasonable correlation between the two test results. Based on the strain level (50%, 100%, or 200%), a threshold value for shear stress can be selected. For example, if a sealant is tested at a specific temperature, and it has a shear stress higher than 180 Pa at 200% strain level, the sealant will pass the criterion for that temperature. Therefore, it was concluded that the yield test can be a good alternative for high-temperature grading of sealants if an appropriate level of stiffness is selected. The stress level of 180 Pa at 200% strain level was selected as a threshold since there is a more clear separation of pass and fail points indicating good consistency between the two methods.



(a) at 50% strain level



(b) at 100% strain level



(c) at 200% strain level

Figure 27. Shear Stress Threshold for Yield Testing at Different Strain Levels

Using the 180 kPa threshold at 200% strain, sealants were graded again for high temperature and correlated with the grade defined by the MSCR test (Table 11). Good correlation was noticed between the two tests. Eight sealants had the same grade defined by both test methods.

Table 11. Crack Sealant High-Temperature Grades Using Yield Test and Correlating to MSCR Test

ID		MSCR Grade (°C)	Yield Grade (°C)	Agreement
Ad		70	70	Yes
Bb		64	76	No
Ca		70	70	Yes
Da		76	76	Yes
Ed		76	76	Yes
Gd		76	76	Yes
Jd		70	70	Yes
Ob		82	82	Yes
Pd		64	76	No
Sd		76	76	Yes
MI	3	64	64	Yes
	4	76	76	Yes
	6	70	70	Yes
	7	82	82	Yes
	12	70	70	Yes
	16	76	70	No

Relationship Between Laboratory and Field Performance

Ambient air temperature for the Michigan sealants was monitored continuously using a data acquisition system installed on the site. The average five hottest days in 2011, 2012, and 2013 are 34.9, 43.2, and 26.8°C, respectively. The performance index (PI) of the six selected crack sealants installed in the Michigan test site was calculated from 2010 onward, as presented in Figure 28 based on overband failure. Most sealant failures resulting from tracking occurred in summer 2012. Sections 12 and 4 were the best performers among the selected sealants while Section 16 was the worst performer, followed by Section 3.

The Michigan test site sealants were also evaluated for high-temperature grading using both MSCR and yield test methods (Table 12). For five out of six sealants, both tests gave the same high-temperature grade. The grade can also be correlated to the field performance as presented in Figure 28 using the criteria considering overband wear. The sealants with PI lower than 70% are categorized as poor performance for the clean and seal sections. For example, sections with relatively low high-temperature grade such as 3 and 16 according to the yield test method demonstrated fair and poor performance. However, the MSCR test showed a relatively high grade for Section 16 (the worst performing section based on overband failure). However, there are also some sealants (6 and 12) with relatively low high-temperature grade but good field performance. The mechanisms of overband wear and it occurs at a wide range of temperatures including winter time during plowing operations. Therefore, it is not expected to get a perfect correlation between high-temperature grade and overband wear type of failure.

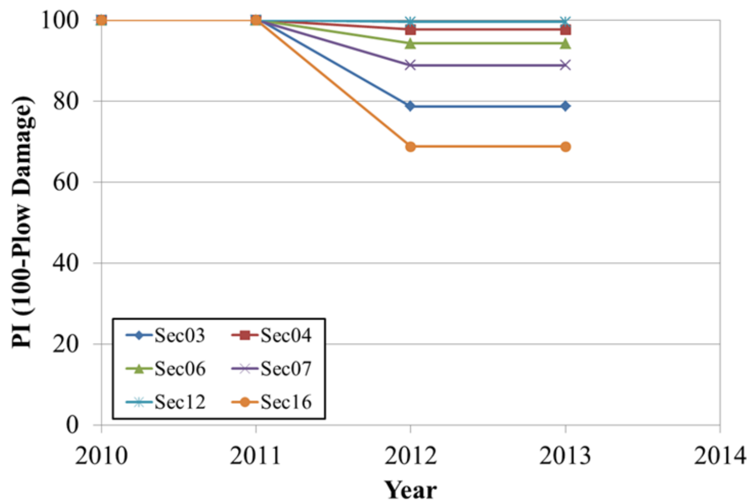


Figure 28. Performance Index of Sealants Based on Overband Failure

Table 12. Field and Lab Performance Correlation for Selected Sealants at Michigan Test Site

Test Section	PI (%)	Field Performance	High-Temperature Grade (°C)	
			MSCR Test	Yield Test
3	78.7	Fair	64	64
4	97.8	Good	76	76
6	94.3	Good	70	70
7	88.9	Good	82	82
12	99.6	Good	70	70
16	68.8	Poor	76	70

Using the DSR to determine sealants high-temperature grade, a good correlation was observed for MSCR and yield test parameters with respect to their SG. Comparing the two tests for high-temperature grade determination, the yield test is recommended as the performance test in relation to both tracking resistance and overband wear due to its simplified approach.

Viscosity

The apparent viscosity test results for all sealants are presented in Figure 29. Based on field observations during installation, the thresholds showed reliability that could ensure sufficient workability during installation at the recommended pouring temperature. However, it is very important not to overheat or underheat sealants.

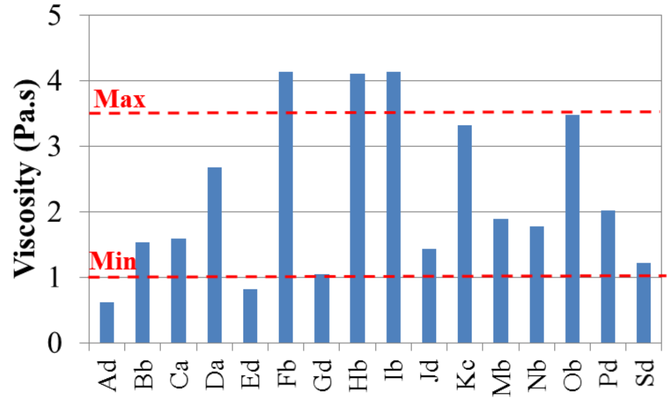


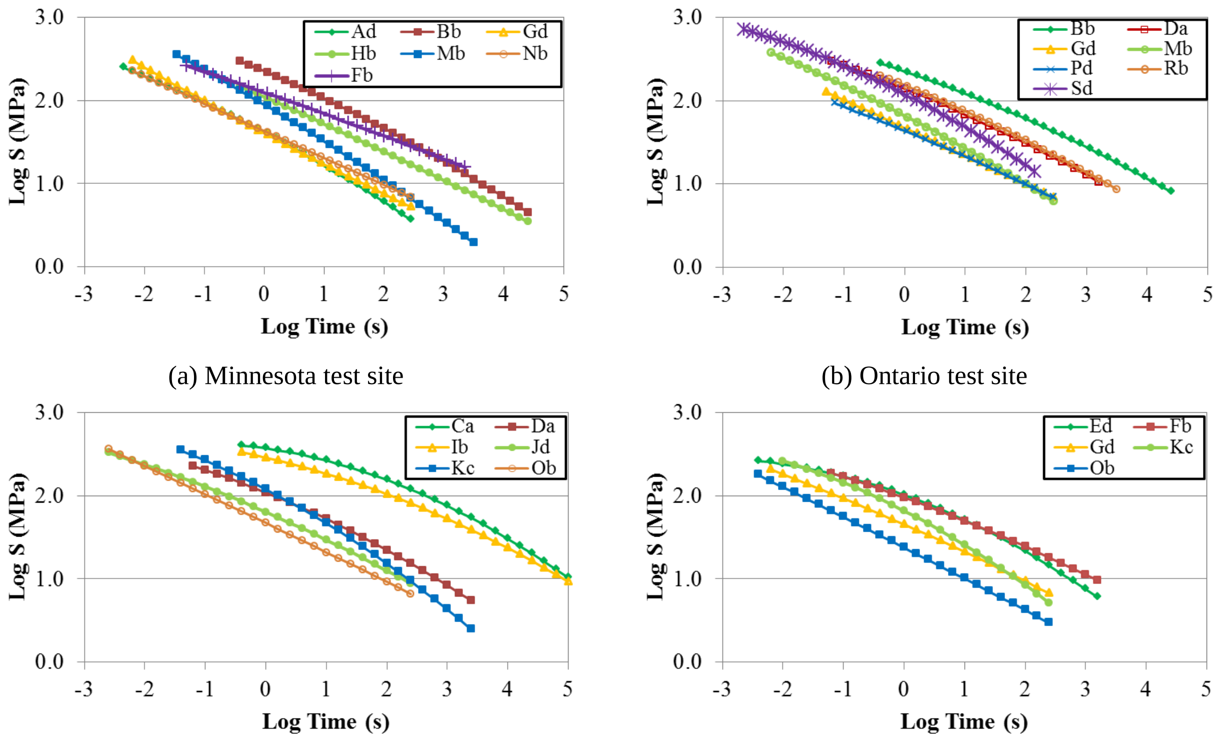
Figure 29. Viscosity Results for All Sealants

Crack Sealant Bending Beam Rheometer

Laboratory Results

During the second and third evaluation periods of each test site, field-aged samples (field-aged second year [FA2] and field-aged third year [FA3]) were collected from each material to be tested in the lab. Results of the CSBBR test for the sealants used in Minnesota, Ontario, New Hampshire, and New York are summarized in Figure 30 using master curves used for viscoelastic characterization. For the analysis, FA2 samples were used for Minnesota and New York sections and FA3 samples were considered for the Ontario and New Hampshire sections. BBR results indicated a wide range of low-temperature stiffness of the materials used in these test sites.

Based on the CSBBR master curves shown in Figure 30, it can be seen that in the Minnesota test site, sealant Bb and Fb had the highest stiffness, followed by sealants Hb and Mb. The stiffness curves for the other three sealants (Ad, Nb, and Gd) exhibited similar characteristics at short loading times. In the Ontario test site, sealant Bb had the highest stiffness while sealant Pd had the lowest stiffness. A wide spectrum of low-temperature stiffness values was evident for the materials used in Ontario. Sealants Ca and Ib had the highest stiffness in New York test site while sealants Ob and Jd had the lowest stiffness. Finally, in the New Hampshire test site, sealants Fb and Ed had the highest stiffness while sealant Ob had the lowest stiffness.



(a) Minnesota test site

(b) Ontario test site

(c) New York test site

(d) New Hampshire test site

Figure 30. Stiffness Master Curves Obtained from CSBBR Test Results at -28°C for Sealants Used in Different Test Sites

Relationship Between Laboratory and Field Performance

The field and lab performance of all sealants installed in the test sites are presented in Table 13. It should be mentioned that the field performance of sealants is related to several factors, including low-temperature stiffness and resistance to cohesive and adhesive failure. Therefore, it was not expected to see a complete correlation between field and CSBBR data at this point. However, for validating the CSBBR test method, the sealants with similar lab performance were expected to be grouped in the same field performance subsets. The same procedure of ranking and grouping was applied to the data collected from all test sites.

The following observations relate specifically to each site:

New York:

- Two of the three soft sealants (Kc and Ob) in Subset A are in the same field performance group (Subset C).
- Sealants with high stiffness (Ib and Ca) are placed in the same group based on their field performance (Subset A).

Table 13. Statistical Grouping of the Sealants in Test Sites Base on Their Field and Lab Performance

Sealant ID	SG (°C)	NY				NH				MN				ON			
		Field Performance		Lab Performance (CSBBR)		Field Performance		Lab Performance (CSBBR)		Field Performance		Lab Performance (CSBBR)		Field Performance		Lab Performance (CSBBR)	
		PI (%)	Statistical Subset[1]	Stiffness (MPa)	Statistical Subset[2]	PI (%)	Statistical Subset	Stiffness (MPa)	Statistical Subset	PI (%)	Statistical Subset	Stiffness (MPa)	Statistical Subset	PI (%)	Statistical Subset	Stiffness (MPa)	Statistical Subset
Ca	-16	20.2	A	119.5	D	-	-	-	-	-	-	-	-	-	-	-	-
Ib	-22	15.1	A	83.1	C	-	-	-	-	-	-	-	-	-	-	-	-
Da	-34	82.7	C	16.4	B	-	-	-	-	-	-	-	-	77.6	D	22.2	B
Jd	-46	78.9	C	8.9	A,B	-	-	-	-	-	-	-	-	-	-	-	-
Kc	-40	35.2	A, B	15.0	A, B	28.7	A,B	5.6	A,B	-	-	-	-	-	-	-	-
Ob	-40	54.0	B	6.6	A	15.7	A	3.1	A	-	-	-	-	-	-	-	-
Ed	-40	-	-	-	-	48.8	C	14.3	C	-	-	-	-	-	-	-	-
Fb	-34	-	-	-	-	30.6	B	18.6	D	95.6	C	29.5	C	-	-	-	-
Gd	-46	-	-	-	-	39.2	B, C	7.1	B	47.0	A	5.7	A	59.2	B, C	7.3	A
Nb	-46	-	-	-	-	-	-	-	-	61.7	A, B	7.1	A	-	-	-	-
Hb	-28	-	-	-	-	-	-	-	-	63.7	A, B	17.6	B	-	-	-	-
Ad	-46	-	-	-	-	-	-	-	-	68.1	A, B	4.0	A	-	-	-	-
Mb	-34	-	-	-	-	-	-	-	-	77.3	B	7.0	A	58.1	B, C	7.1	A
Bb	-28	-	-	-	-	-	-	-	-	77.0	B	33.2	C	32.4	A	43.3	C
Pd	-40	-	-	-	-	-	-	-	-	-	-	-	-	43.7	A, B	7.1	A
Rb	NA	-	-	-	-	-	-	-	-	-	-	-	-	69.3	C, D	24.1	B
Sd	-40	-	-	-	-	-	-	-	-	-	-	-	-	79.1	D	10.8	A

[1] Statistical groups for field performance are represented with letters: "A" (lowest rank performer) to "C" or "D" (highest rank performer).
[2] Statistical groups for lab performance are represented with letters: "A" (lowest stiffness) to "C" or "D" (highest stiffness).

Minnesota:

- Sealants with lower stiffness values (Gd, Nb, and Ad) are in the same subset for both field and lab performance. Subset A for field performance includes sealants with a PI lower than the passing threshold (PI < 70%).
- Sealants Fb and Bb with a significantly higher stiffness are grouped in the field subsets having relatively high PI.

Ontario:

- Sealants with lowest stiffness (Gd, Pd, Mb, and Sd) are grouped in the same subset (Subset A). Except for Sd, three other sealants share the same subset, based on their field performance (Subset B).
- Sealants with high stiffness (Rb and Da), which are grouped in a different subset than soft sealants (Subset B), fall in the same group based on their field performance (Subset D).
- Among these sealants, Bb had the highest stiffness and the lowest PI. This observation is significant for the validation of the maximum stiffness threshold to ensure field performance.

New Hampshire:

- A similar trend was also observed for the five different sealants installed at this test site. The soft sealants (Ob and Kc) in Subset A are in the same field performance group (Subset A).

In general, a correlation was observed between sealants stiffness and field performance in all four test sites. The statistical groups with similar stiffness and PI were consistent. A comparison between field PI and sealants stiffness is presented in Figure 31, which can clearly be divided to three zones with distinctive sealants performance characteristics:

- Zone 1: Sealants with fair field performance (50% < PI < 70%) and low stiffness
- Zone 2: Sealants with good field performance (PI > 70 %) with moderate stiffness
- Zone 3: Sealants with poor field performance (PI < 50%) and high stiffness

The data provided in Figure 31 can be used as experimental support for defining stiffness threshold values to ensure good field performance of the sealants. There is a need to define two thresholds to avoid using sealants that are either too soft or too stiff.

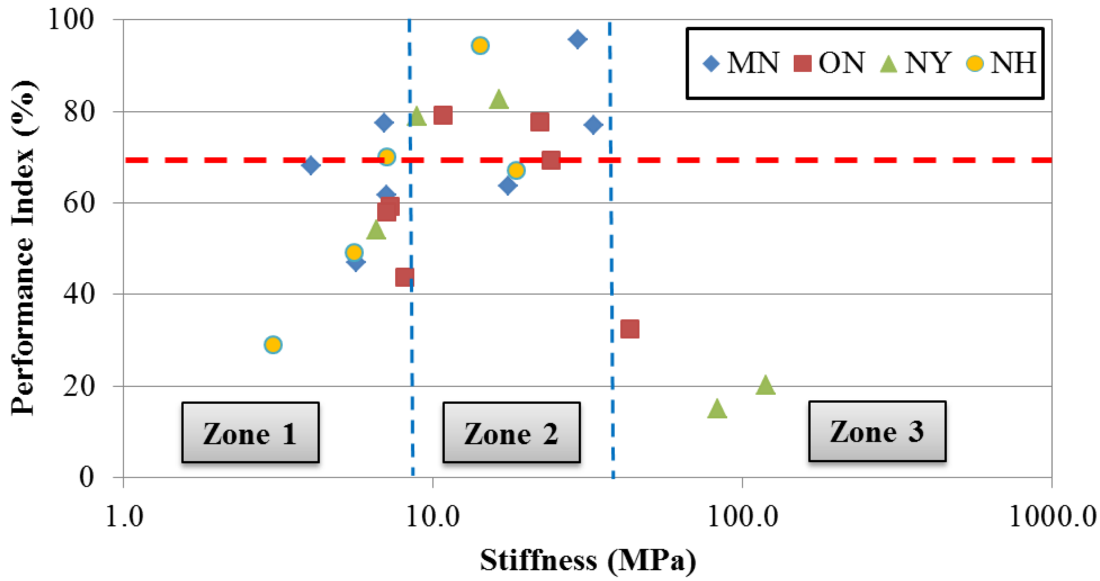


Figure 31. Correlation Between Field Performance Index (PI) and a Sealant's Temperature Stiffness at -28 °C for the Materials Installed in Four Test Sites

Crack Sealant Direct Tension Test

Since direct tension test is expected to be related to sealant's cohesive performance only, clean and seal sections in Michigan and New York were used to validate the CSDTT threshold values.

Laboratory Results

Following the AASHTO TP 87 and AASHTO TP 88 provisional standards, six selected sealants were aged and tested in the lab to obtain their CSBBR and CSDTT parameters and grade (Table 14). Five out of six crack sealants had an extendibility higher than 89% at the grading temperature. The Michigan test section consisted of only clean and seal treated cracks. Therefore, field-aged materials were not collected. Testing was conducted using laboratory-aged sealants only.

Table 14. Summary of CSDTT Test Parameters for the Selected Sealants in Michigan Test Site

Section (ID)	Test Temperature (°C)	Max. Load (N)	Extendibility	Extendibility Threshold	SG Based on CSBBR (°C)	Confirmed SG (°C)
3	-34	31.8	97%	85%	≥-40	-40
4	-22	24.6	95%	55%	≥-28	-28
6	-34	19.4	95%	85%	≥-40	-40
7	-4	13.7	15%	10%	≥-10	-10
12	-34	31	92%	85%	≥-40	-40
16	-22	17.1	89%	55%	≥-28	-28

Relationship Between Laboratory and Field Performance

CSDTT results were further analyzed using the Tukey test to categorize sealants in different subsets based on extendibility and maximum load as reported in Table 15. Different subsets of sealants were obtained for the extendibility. The correlation table between low-temperature extendibility and cohesive failure (Table 15) shows that the three sealants with maximum extendibility (98%) were placed in the same statistical group and had good field performance based on cohesive failure. The other three sealants with extendibility lower than threshold (75% at -28°C) had fair (70% < PI < 90%) performance.

CSDTT maximum load was also correlated to the cohesive failure (Table 16). It was concluded that sealants with greater maximum loads tend to be more brittle and the value of PI decreases with the increase in the load.

Table 15. Statistical Grouping of the Sealants Based on CSDTT Extendibility and Cohesive Failure

Sealant ID	Extendibility at -28°C			Field Performance		
				Cohesive Failure		
	%	Statistical Subset	Status	PI (%)	Subset	Performance
3	98.6	A	**Pass**	90.3	A, B	**Good**
6	98.6	A	**Pass**	98.3	A	**Good**
12	98.6	A	**Pass**	97.9	A	**Good**
16	43.9	B	**Fail**	80.5	B	**Fair**
4	6.9	C	**Fail**	88.8	B	**Fair**
7	1.3	C	**Fail**	74.9	B	**Fair**

Table 16. Statistical Grouping of the Sealants Based on CSDTT Maximum Load and Cohesive Failure

Sealant ID	Maximum Load at -28°C			Field Performance		
				Cohesive Failure		
	N	Statistical Subset	Status	PI (%)	Subset	Performance
6	9	A	**Pass**	98.3	A	**Good**
3	15.7	A, B	**Pass**	90.3	A, B	**Good**
12	19.2	B	**Pass**	97.9	A	**Good**
16	34.2	C	**Fail**	80.5	B	**Fair**
4	36.3	C	**Fail**	88.8	B	**Fair**
7	45.4	D	**Fail**	74.9	B	**Fair**

Similar to the Michigan test site, PI of clean and seal sections from the New York test site was correlated with the laboratory performance data shown in Table 17. It can be seen that the sealants Jd and Ob, belonging to the same subset for having high extendibility (higher than 70%), demonstrated good field performance in 2013. On the other hand, sealants Ca and Ib, belonging to the same statistical groups, failed in 2013 just after a winter season due to low extendibility. However, sealants Kc and Da had low extendibility, but good field performance in 2013. The maximum load and tensile failure energy, which considers the effect of both load and extendibility, showed similar trends to extendibility.

Table 17. Statistical Grouping of the Sealants Based on CSDTT Extendibility and PI in New York Test Site

Sealant ID	Extendibility			Field Performance (2013)			Field Performance (2014)		
	%	Statistical Subset	Status	PI (%)	Subset	Performance	PI (%)	Subset	Performance
Ca	2.4	A	Fail	50.8	A	Poor	5.4	A, B	Poor
Ib	2.7	A	Fail	32.2	A	Poor	0	A	Poor
Da	13.4	A, B	Fail	84.4	A, B	Good	13.9	B	Poor
Kc	27.5	B	Fail	90.3	B	Good	24	B	Poor
Jd	72	C	Pass	76.3	A, B	Good	14.3	A, B	Poor
Ob	91.2	C	Pass	71.5	A	Good	14.3	B	Poor

Based on observations for the two test sites, each including six clean and seal sections, acceptable correlation to the field performance was found between the extendibility test parameter. Other test parameters such as maximum load and tensile energy can also be used to support sealant cohesive characterization in relation to field performance.

Modified Crack Sealant Adhesion Test

Evaluation

Repeatability. The modified adhesion test was repeated with multiple specimens to evaluate its variability. The repeatability of the elastic energy and peak load parameters was investigated by evaluating the CoV for different sealants at different temperatures using multiple replicates and different operators. Repeatability among replicate tests for a highly crumb rubber-modified sealant was improved significantly as compared with the previous version of the adhesion test. The improvement in the repeatability of load-displacement curves is apparent with the modified test. The results also showed that specimen mishandling may have limited impact on results due to the high peak loads obtained through testing. The tests show that as sealant becomes more brittle (at low temperature), variations increase.

The sealant peak load CoV was less than 20%. The CoV for the elastic fracture energy results was relatively higher, but for most cases it was less than 35%. Repeatability of the modified adhesion test was deemed sufficient considering the fact that this is a failure test and more variation is expected. In conclusion, peak loads can be more reproducible with relatively lower variability. Therefore, the peak load was selected as an adhesive parameter and considered in this study.

Discrimination Potential. An evaluation was also conducted to determine whether this test can provide a range of results that can group good and poor performing sealants. Various types of sealants were tested. Figure 32 shows a comparison of four sealants tested at multiple temperatures. Unlike the CSAT where all adhesive loads are within the same range, modified adhesion test shows clearly that laboratory adhesive performance of these four sealants is significantly different. Peak load in the modified test depends on temperature and varied from 20 to 400 N. Elastic fracture energy results show a dependence on temperature as well. In addition, at the same temperature, sealants may have different adhesive performance depending on their composition. The discrimination potential can be seen clearly in Figure 32, where various sealants behave differently at the same temperature (e.g., Sealants Ad and Kc at -34°C). The peak load and elastic fracture energy may have the same trend, but it is sealant type-dependent. It can be concluded that the modified adhesion test provides a good range of results to discriminate among the sealants.

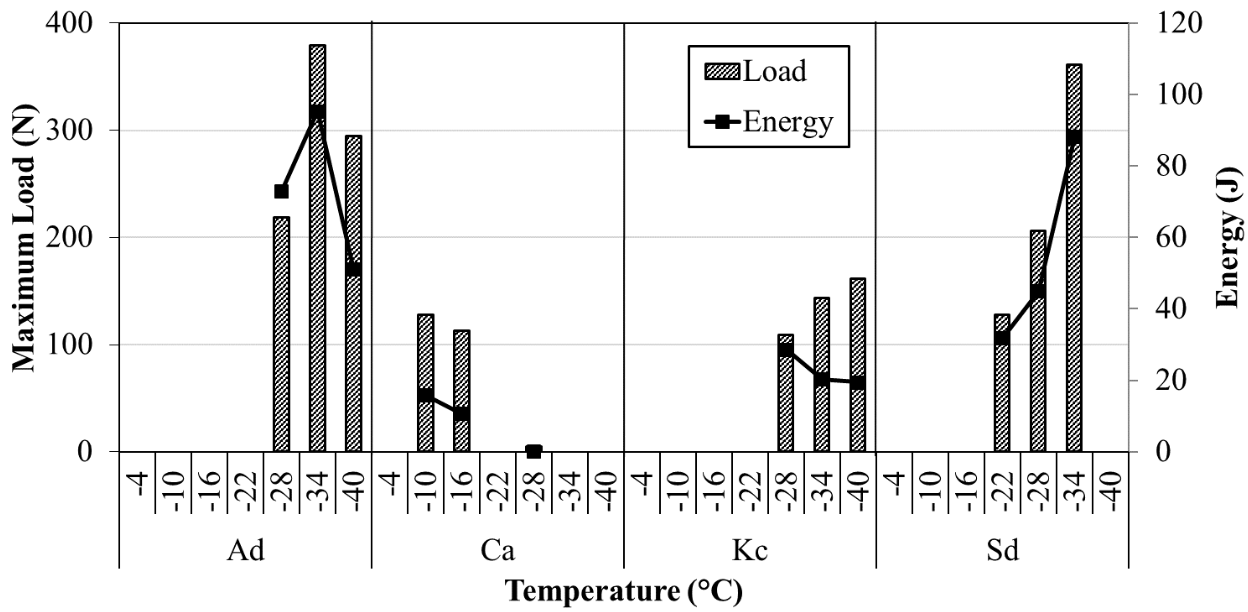


Figure 32. Distinctive Adhesive Behavior as a Function of Temperature for Four Crack Sealants

Validation

Modified adhesion test results were used to correlate laboratory adhesive characteristics and sealant field performance. In general, results show a good correlation between peak loads and the PI for the tested sealants. This correlation was investigated through statistical analysis. Most of the test sites showed an acceptable correlation between lab test results and field performance.

Figure 33 shows the overall comparison of laboratory adhesion and field performance. The comparison shows that there is correlation between the adhesion peak load and the PI. In addition to the overall correlation, there seems to be two groups of sealants with distinct adhesive characteristics: one is the low performing group with adhesive peak loads less than 20 N, which has poor field performance; and the other is the group of sealants with adhesive peak loads between 200 and 400 N, which demonstrates a correlation between field and lab adhesive performance. Field-to-lab correlation showed that sealants with low adhesive characteristics are among the poor performing sealants in the field. The results obtained from the proposed adhesion test and correlation to field performance show that sealants should have good adhesive characteristics as a starting point regardless of other properties (such as stiffness, extendibility, etc.) to have a good field performance or avoid premature failures.

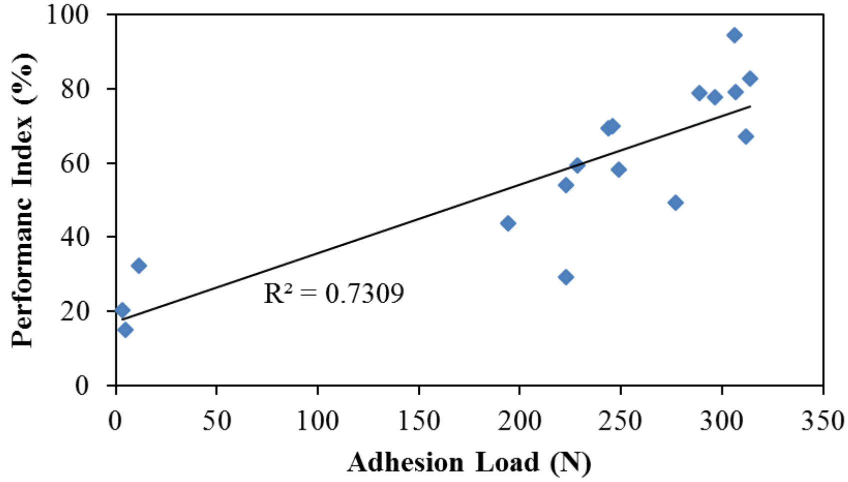


Figure 33. Correlation between Performance Index and Adhesion Peak Load

DISCUSSION

Field Performance in Relation to Laboratory Test Results

Generally Observed Trends

Low-temperature test parameters and their expected relationships with field performance are summarized in Table 18. Cohesive failure was the main failure type observed in clean and seal treatments, while adhesive failure was the main failure type observed in rout and seal treatments. Field correlation results showed that the CSBBR parameters (stiffness and ACR) are related to good sealant durability. Thus, higher relaxation potential (represented by high ACR values) is required to ensure a good flexibility rate of the material against deformation. Stiffness is the major characteristic that reduces the stress build up during crack movements within the material, material interface, and rout wall. The parameters obtained from the CSBBR test could be related to both adhesive and cohesive failures as the stiffness parameter also reflects the overall characteristics of sealants related to formulations and field performance.

The CSAT simulates adhesion performance in the rout and seal configurations. The parameters that can be obtained are maximum adhesion load and interfacial energy. Higher peak loads and higher adhesive energy are desired for a good bonding between the sealant and rout wall. Finally, CSDTT test method is needed to ensure good cohesive properties of the sealants for clean and seal treatments. Therefore, high extendibility and tensile energy should result in better field performance. Field observations support the following grading schemes for the two types of sealing treatments:

- Rout and seal: Primary test is the CSBBR test (stiffness and ACR parameters) and secondary test is the adhesion test (the CSAT and maximum adhesion load parameter)
- Clean and seal: Primary test is the CSBBR test (stiffness and ACR parameters) and secondary test is the direct tension test (the CSDTT and extendibility parameter)

Table 18. Test Parameters and Expected Trends with Field Performance

Test Method	Test Parameter	Expected Trend with Field Performance	Mechanism	Application
CSBBR (AASHTO TP 87)	Stiffness at 240 sec	Inverse	Increasing stiffness and higher stresses in the sealant	Required for both rout & seal and clean & seal
	Average Creep Rate	Proportional	Lower ACR and higher stresses in the sealant	Required for both rout & seal and clean & seal
CSAT (AASHTO TP 89)	Peak Load	Proportional	Increasing adhesive load and stronger bond between sealant and rout's wall	Required for rout & seal
	Interfacial Energy (optional)	Proportional	Increasing energy and work of adhesion	Required for rout & seal
CSDTT (AASHTO TP 88)	Extendibility	Proportional	High elongations and large crack openings	Required for clean & seal
	Dissipated Energy (optional)	Proportional	Increasing energy and better tensile work	Required for clean & seal

Based on the laboratory performance and correlation with field performance, sealants were categorized into three general groups. Table 19 presents the average climatic conditions observed in the majority of test site installations to illustrate the most critical testing parameters that have a defining role in the field performance. It appears that adhesion and stiffness are the two most critical parameters. In general, it was observed that when adhesion capacity is low, the risk of premature failure is high, accompanied by crack openings as well as excessive stiff characteristics of sealants (2 or more grades warmer). The best performing sealants are the ones with high adhesion capacity and moderate stiffness, depending on the climate they are installed in. The medium performing group are those with soft sealants (1 or 2 grades colder) and moderate adhesion. Additional mobility was observed in this group, thus indicating moving upward and downwards in the ranks depending on the installation quality and on-site conditions affecting crack movements such as crack length and pavement type and materials.

Another observation from the information provided in the table is the correlation between adhesion and stiffness. As sealant stiffness increases or decreases, adhesion capacity changes indicating an optimum adhesion performance that can be obtained from sealant formulation. In Table 19 the first group includes sealants with poor field performance (PI < 50%). These sealants had some common characteristics. Depending on the site they were installed in, the sealants in this group demonstrated high stiffness and low adhesive properties. The majority of sealants were in the second group with fair field performance (50% < PI < 70%). Most of these sealants have low stiffness (except Fb and Ed) with respect to test site requirements. Except for sealant Pd, the sealants in this group have an acceptable adhesive load at the test site temperature. Therefore, their fair performance can be related to the low stiffness and resistance to wear and abrasion. Low CSBBR stiffness means low resistance against plows and early failure of the overband, which exposes the sealant and rout interface and potentially accelerates adhesive failure. It is important to note that the performance of some sealants in this category could be lower or higher depending on the on-site conditions such as crack length, pavement and initial crack condition, as well as the installation quality. The third group includes sealants that have moderate stiffness and good adhesive performance. This is the ideal combination for a sealant to survive longer in the field. Subsequently, these sealants also have good field performance (PI > 70%).

Table 19. Overall Sealant Grouping Based on Expected Field Performance for Sites at Moderately Cold Climate Regions (-28 to -34 °C)

Sealant ID	Test Site	Field Performance	Adhesion Load	Stiffness Property	Remarks
Bb	ON, MN, WI	Group 1: Poor (PI less than 50%)	Low	High	Sealants having high stiffness AND low adhesive capacity. Failure mechanism could be due to low adhesion or excessive stiffness with respect to the climate they are installed.
Ca	NY		Low	High	
Hb	MN		Low	High	
Ib	NY		Low	High	
Kc	NY, NH		Low	High	
Ad	MN, WI	Group 2: Fair (PI between 50% and 70%)	Medium	Low	Sealants with low stiffness AND moderate adhesion capacity. Overband failure common in those sealants. Some mobility upwards or downwards is expected with installation quality and on-site conditions
Ed[2]	NH, WI		Medium	Low	
Fb[2]	MN, NH, WI		Medium	Medium	
Gd	MN, ON, NH		Medium	Low	
Mb	MN, ON		Medium	Low	
Nb	MN		Medium	Low	
Ob	NH, NY		Medium	Low	
Pd[1]	ON, WI		Low	Low	
Sd	ON	Group 3: Good (PI higher than 70%)	High	Medium	Sealants with moderate stiffness AND good adhesion capacity. Candidates for the best performance for this climate.
Da	ON, NY		High	Medium	
Jd	NY		High	Medium	
Rb	ON		High	Medium	

[1] Sealant Pd can switch to a low performing type depending on the on-site conditions and installation quality.
[2] Sealants Fb and Ed were among the relatively high performing subset of medium performing sealants. Depending on the on-site conditions and installation quality, these two sealants can switch to high performing group.

Correlation Score

A holistic evaluation method is required to evaluate which laboratory test methods have the best correlation to field performance. Different statistical tests were used to develop a composite score and to establish a quantitative correlation based on sealant field performance (PI) compared with different parameters, such as flexural stiffness and ACR from the CSBBR method, peak load from CSAT method, and peak load and extendibility from CSDTT method. Two different statistical correlation techniques were used: Kendall's tau-b, and regression (linear or quadratic). Kendall's tau-b is a test for independence and correlates PI with test parameters based on ranking. The regression method correlates field and lab based on their values. The Kendall's tau-b measure of association is a distribution-free, or non-parametric, rank correlation parameter. The Kendall's parameter is better suited to small datasets than is the correlation coefficient, R, or the coefficient of determination, R^2, which are more appropriate for larger datasets.

The composite score is developed based on Gibson et al. (2012) as follows:

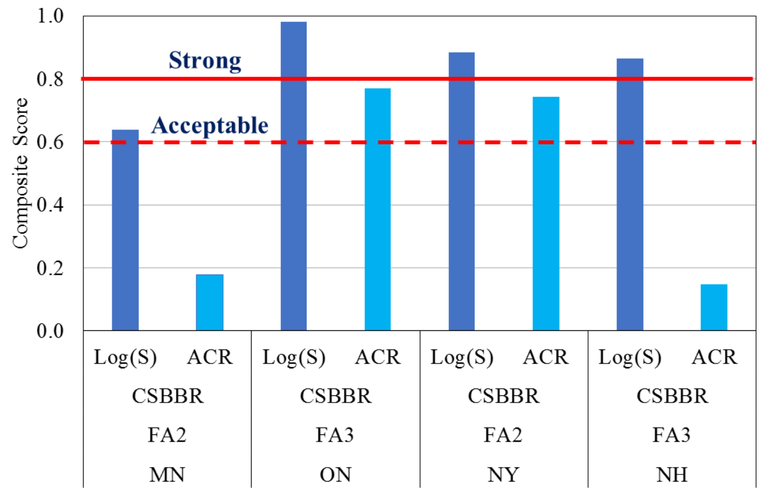
$$CS = \frac{|R|+(1-P_R)+|\tau_K|+(1-P_K)}{4} \tag{6}$$

where

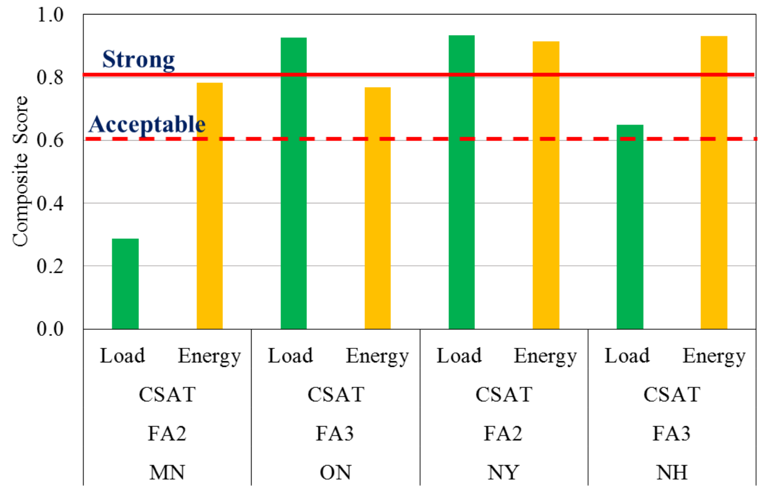
CS = Composite score (0 for no correlation and 1 for complete correlation)
R = Regression coefficient
τ_K= Kendall's tau-b measure of association score, $-1 < \tau_K < 1$
P_R= ANOVA significance of the regression slope
P_K= Significance of the Kendall's tau-b association

Using these parameters, the composite score is calculated for clean and seal as well as rout and seal sections. For rout and seal sections, the scores of CSAT and CSBBR parameters were evaluated while for clean and seal sections the scores were calculated for CSDTT and CSBBR parameters. The following thresholds were used to identify satisfactory levels of correlation. A score higher than 0.60 is considered acceptable; if the score is higher than 0.80, then a strong correlation between the parameters is assumed. Composite scores for different test parameters with their corresponding PI are presented in Figure 34. The low-temperature stiffness parameter obtained from the CSBBR test (Figure 34a) has a strong correlation with the field performance (except the Minnesota test site, which has an acceptable correlation score). However, the score for ACR is either acceptable or poor. Adhesion peak load and energy, except for the sealants at the Minnesota test site, have an acceptable or a strong correlation score with the field performance (Figure 34b).

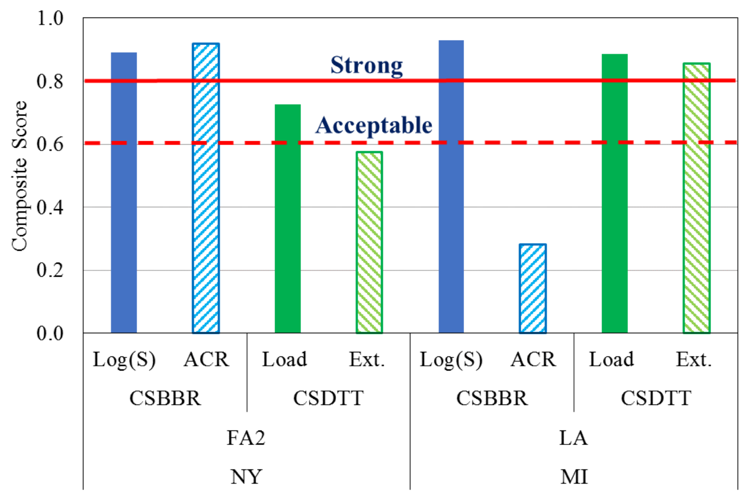
For the clean and seal sections, the composite score is calculated for the parameters obtained from CSDTT and CSBBR methods for New York and Michigan test sites. The scores presented in Figure 34c shows that, similar to the rout and seal sections, stiffness has a strong correlation with field performance. However, ACR either had a strong or very poor score. For the CSDTT test parameters, both peak load and extendibility had an acceptable or strong score.



(a) CSBBR test parameters score compared with rout and seal (R&S) PI



(b) CSAT test parameters compared with rout and seal (R&S) PI



(c) CSBBR and CSDTT test parameters compared with clean and seal (C&S) PI

Figure 34. Composite Score Correlating Test Parameters with PI for R&S and C&S Sections

CSBBR Performance Thresholds

A comparison between field PI and sealant stiffness for all test sites clearly showed three zones with distinctive sealant performance characteristics: Zone 1 in which sealants had fair field performance (50% < PI < 70%) and low stiffness; Zone 2 in which sealants had acceptable field performance (PI > 70%) with moderate stiffness values; and Zone 3 in which sealants had poor field performance (PI < 50%) but high stiffness. Based on these zones, two-tiered thresholds were introduced: minimum and maximum stiffness measured by the CSBBR test method.

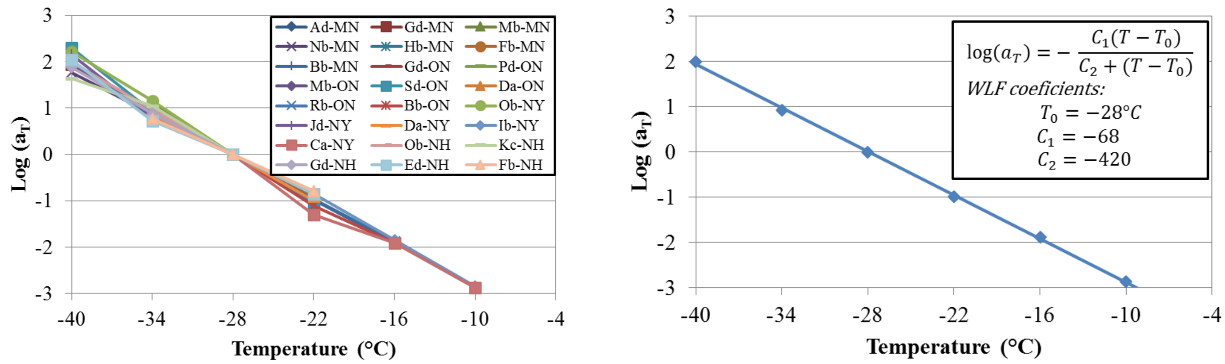
Maximum Stiffness

A maximum threshold for stiffness must be set to ensure the flexibility of crack sealant at low temperature due to thermal loading caused by crack opening. During field installation, a wireless temperature node was installed at each test site to monitor air temperature during the evaluation period. Using the temperature log, a maximum threshold is defined for each test site. Then, based on the threshold value measured for each test site, final threshold for maximum allowable stiffness is selected.

Based on the test site temperature log, the average lowest temperatures for the five coldest days during the critical winter are -22.2, -29.2, -20.3, and -23.8°C for Minnesota, Ontario, New York, and New Hampshire, respectively. The average of these 5 days was used to obtain the thresholds.

To fine-tune the maximum threshold, sealant properties should be measured or calculated at the actual field low temperature. CSBBR stiffness master curves obtained from three different temperatures were shifted to the low test site temperature and the stiffness was extracted at proper thermal loading time. All shift factors used to calculate the master curves for the field-aged samples are presented in Figure 35a. Based on the average shift factors considering the sealants tested herein, it is observed that almost every 6°C in temperature shifting is equal to a decade of shifting in loading time (Figure 35b). Based on the CSBBR test method, sealants should be tested to determine stiffness at 240 sec and at a temperature of 6°C higher than their low-temperature grade. Therefore, the stiffness at 240 sec at the testing temperature would be equivalent to the stiffness of the same sealant at 2400 sec at grading temperature. Hence, stiffness values for the sealants with highest stiffness at different test sites were calculated from the master curves at 2400 sec at the average test site low temperature and correlated with the field PI in Table 20.

A sealant with a PI less than 70% was considered a failing sealant. For specific test sites, such as Minnesota and New Hampshire, none of the sealants failed due to high stiffness. Other reasons could contribute to sealants poor field performance; including poor adhesion bonding or very soft sealant at low temperatures.



(a) All shift factors to obtain master curves (b) Reference shift factor curve

Figure 35. Shift Factors for All Field-Aged Sealants to Obtain Master Curve at -28°C

Three sealants demonstrated poor performance as a result of high stiffness (Ib and Ca at the New York test site and Bb at the Ontario test site). Stiffness obtained from the CSBBR test and PI for these sealants is summarized in Table 20. Based on lab and field correlation, the high stiffness threshold measured at 240 sec of creep loading can be selected as 15 MPa at the testing temperature (6°C below grading temperature), which is lower than the initial threshold (25 MPa) selected during test development.

Table 20. Field and Lab Correlation for Sealants Failing due to High Stiffness

Sealant ID	Test Site	CSBBR Stiffness at Real Test Temperature (MPa)[1]	CSBBR Stiffness at Test Site Low Temperature (MPa)[2]	Performance Index (PI)	Status
Ib	NY	19.1	14.4	15.1	**Fail**
Ca	NY	22.0	14.8	20.2	**Fail**
Bb	ON	18.2	22.7	32.4	**Fail**
Da	ON	10.7	10.9	77.6	**Pass**
Rb	ON	8.96	12.0	69.3	**Pass**

[1] Stiffness is obtained from stiffness master curve by shifting to the actual test site temperature.
[2] Stiffness is obtained from the test temperature based on the test site sealant grade.

Minimum Stiffness

Based on field results, it was observed that some sealants could have failed due to their low stiffness. During the winter snow plowing combined with traffic shear loading may cause damage to sealants by applying high amounts of shear stresses at low speeds. Vehicular loading can also contribute to wearing of sealants. Sealants with low stiffness would not have enough resistance against the applied shear loading and this would lead to overband loss. It was observed earlier that overband has a significant effect on the performance of sealants. Therefore, a minimum stiffness threshold should be identified for sealants to assure their resistance to plow damage.

To determine the minimum threshold, the shear rate applied to the sealants by plow must first be calculated. Shear rate is the ratio of loading speed to thickness of the material:

$$\dot{\gamma} = {}^{V}\!/_{h} \tag{7}$$

Assuming a plow speed of 8.94 m/sec (20 mph) and a typical rout depth of 20 mm, the shear rate will be 447 sec^{-1}. Hence, loading time will be equal to 0.0022 sec. The minimum threshold is obtained by correlating the stiffness values identified from the CSBBR master curves at low temperature with the PI. The summary of field and lab data for the sealants failing due to their low stiffness in all test sites is presented in Table 21. Based on these results, the minimum stiffness can be defined as 210 MPa at real loading time (0.0022 sec). Stiffness of sealants to withstand loading rate applied by plows was extracted from the master curves developed using the CSBBR test. A practical loading time in the CSBBR test is then needed to correlate with relatively fast loading rates applied in the field and resulting in overband wear. Thus, the corresponding stiffness in the CSBBR is also calculated in the first second at the testing temperature that represents sealants resistance to faster loading rates (Table 21). Based on the lab and field correlation, it can be concluded that the low stiffness threshold measured at 1 sec of creep loading should be more than 40 MPa at the testing temperature.

Table 21. Field and Lab Correlation for Sealants Failing Due to Low Stiffness

Sealant ID	Test Site	PI (%)	CSBBR Stiffness (MPa) at 0.0022 sec at Real Temperature[1]	CSBBR Stiffness (MPa) at 1 sec at Test Temperature[2]	Status
Ob	NY	54.0	128.8	18	**Fail**
Gd	MN	47.0	194.0	39	**Fail**
Nb	MN	61.7	168.8	21	**Fail**
Ad	MN	68.1	157.0	< 40	**Fail**
Sd	ON	79.1	> 750	92	**Pass**
Mb	MN	77.3	244.4	74	**Pass**
Da	NY	82.7	266.2	69	**Pass**

[1] Stiffness is obtained from stiffness master curve by shifting to the actual test site temperature.
[2] Stiffness is obtained from the test temperature based on the test site sealant grade.

CSDTT Performance Thresholds

Similar to the CSBBR test method, CSDTT was validated using the correlation of field and lab performance. Then, the parameters and thresholds were fine-tuned using the same field performance and laboratory performance data of sealants.

Field and lab correlation showed that sealants passing the extendibility threshold also performed well in the field. However, field and lab correlation showed that some sealants may fail the extendibility threshold, but have acceptable field performance (sealant Kc and Da in New York test site). In this case, the load can be defined as a secondary threshold. CSDTT tensile load might indicate sealant brittleness; the higher the tensile load, the more brittle the sealant. Brittle sealants are not appropriate for clean and seal treatment. Peak tensile load for the sealants treated as clean and seal is plotted based on their PI in Figure 36. This plot shows that sealants with a peak tensile load higher than 25 N had poor field performance; this value could be used as an additional optional threshold for the CSDTT method.

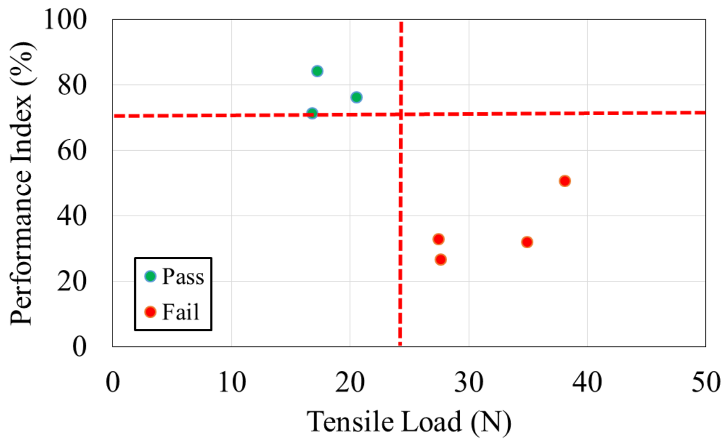


Figure 36. Sealants CSDTT Tensile Load vs. Performance Index

CSAT Performance Thresholds

The new adhesion test showed that there is very good correlation between the peak adhesion load and field performance. Previously, the threshold was set at 50 N for all sealants at all temperatures. Due to unpredictable changes in sealant adhesion load with temperature and changing interfacial loads with decreasing temperatures, a single value of threshold was deemed inappropriate. A multi-temperature testing and corresponding threshold is adopted similar to CSBBR protocol. To simplify the characterization process, an envelope type of threshold was suggested for peak loads.

In colder temperatures, pavement openings enlarge. This enlargement induces stresses within the sealant as well as to the interface. While these stresses are negligible to the pavement itself, they are significant for the low modulus sealants. These stresses increase as the temperature drops. For good sealant performance, sealants should acquire certain adhesive and cohesive characteristics to withstand these stresses. Adhesive failures occur when the interface stresses exceed the capacity of the interface adhesion (sealant-to-pavement wall). Since pavement opening is the driving factor, the sealant and the interface are exposed to larger displacements at colder temperatures. A sealant's ability to expand reduces as the temperature drops. This induces larger interface strains to accommodate the larger pavement opening at colder temperature, thus generating higher interface stresses and rendering sealants more prone to adhesion failures. As a result, the suggested approach was to assign a lower threshold at higher temperatures since the interface loads are lower compared with cold temperatures.

Further investigation and correlating with sealant field performance revealed that the threshold is capable of capturing the worst sealants in the field. The selected threshold is shown in Figure 37 and presented in Table 22.

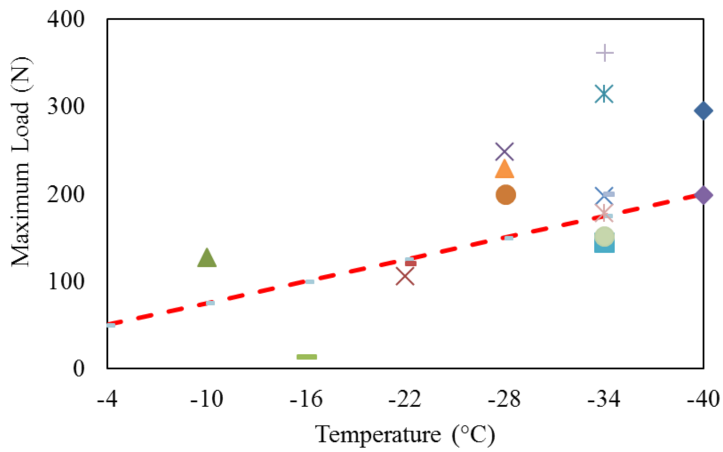


Figure 37. Selected Envelope for Sealant Peak Adhesion Load

Table 22. CSAT Peak Load Thresholds at Different Temperatures

Temperature (°C)	-4	-10	-16	-22	-28	-34	-40
Peak Load (N)	50	75	100	125	150	175	200

Sealant Grading with New Thresholds

All sealants in the test matrix are graded using low-temperature tests based on the new thresholds summarized in Table 23 and reported in Table 24. The new grading procedure requires the reporting of two grades: one for rout and seal treatment, and the other for clean and seal treatment. If the treatment selected is clean and seal, sealants should be graded using CSBBR and CSDTT, and if rout and seal treatment is selected, sealants should be graded using CSBBR and CSAT.

Table 23. Summary of the New and Old Thresholds for Low-Temperature Tests

Test Method	Test Parameter	Treatment Type	Criterion	Threshold	
				Phase I	**Phase II**
CSBBR	Max. Stiffness	C&S R&S	@ 240 sec @Temp 6°C Higher Than Grade	25 MPa	15 MPa
	Min. Stiffness	C&S R&S	@ 1 sec @ Temp 6°C Higher Than Grade	N.A.	40 MPa
	ACR	C&S R&S	@Temp 6°C Higher Than Grade	0.31	0.31
CSDTT	Extendibility	C&S	@ Max/Failure Load @Temp 6°C Higher Than Grade	Diff. % at Grade	Same as Phase I
	Load	C&S	Maximum/Failure Load	N.A.	25 N
CSAT	Min. Load	R&S	@Temp 6°C Higher Than Grade	50 N	50 N (@ -4°C) + 25/-6°C

The SG based on LTPPbind required for different test sites is listed in Table 25. It should be noted that these grades are based on ambient temperature and not pavement temperature.

Most failures in crack sealants are initiated at the top of the sealant, which is open to weathering as well as the overband. Therefore, using the ambient temperature for grading will be a conservative approach.

Table 24. Low SG Based on Fine-Tuned Thresholds

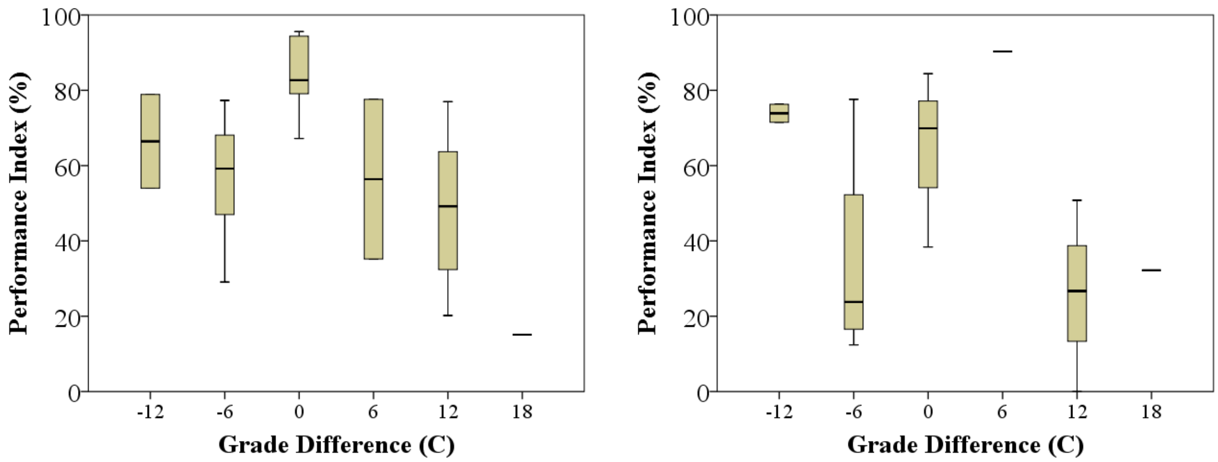
ID		Rout and Seal Low-Temperature Grade (°C)			Clean and Seal Low-Temperature Grade (°C)			Initial SG (°C)
		CSBBR	CSAT	Overall	CSBBR	CSDTT	Overall	
1	Ad	-40	-46	-40	-40	-46	-40	-40
2	Bb	-22	-22	-22	-22	-16	-16	-16
3	Ca	-16	-22	-16	-16	-10	-10	-10
4	Da	-28	-40	-28	-28	-34	-28	-34
5	Ed	-34	-46	-34	-34	-40	-34	-40
6	Fb	-34	-40	-34	-34	-34	-34	-34
7	Gd	-40	-40	-40	-40	-46	-40	-34
8	Hb	-28	-22	-22	-28	-22	-22	-22
9	Ib	-16	-10	-10	-16	-10	-10	-10
10	Lb[1]	NA	NA	NA	NA	NA	NA	NA
11	Jd	-46	-40	-40	-46	-46	-46	-46
12	Kc	-34	-22	-22	-34	-28	-28	-28
13	Mb	-34	-40	-34	-34	-40	-34	-34
14	Nb	-40	-40	-40	-40	-40	-40	-34
15	Ob	-40	-40	-40	-40	-40	-40	-40
16	Pd	-40	-40	-40	-40	-28	-28	-28
17	Rb[1]	NA	NA	NA	NA	NA	NA	NA
18	Sd	-34	-40	-34	-34	-34	-34	-34

[1] Virgin samples were not available to be aged and graded in the laboratory.

Table 25.Required SG for Test Sites Based on the LTTPbind software

Test Site Location	Ambient (°C)		Low SG (°C)
	Min	Max	
Belleville, Wisconsin	-28.9	32	-34
St Charles, Minnesota	-31	31.1	-34
Lindsay, Ontario, CA	-28.7	29.7	-34
Grantham, New Hampshire	-29.1	31.9	-34
Canandaigua, New York	-24	30.9	-28

Statistical boxplots are generated based on the grade difference (sealant SG and required grade for the test sites) for each sealant and its performance index. For rout and seal sections, Figure 38a shows that sealants at the right grade (with no grade difference) perform well at the test sites. Sealants at a grade higher than that required for the test site (positive grade difference) fail in the lab due to high stiffness, low adhesion load, or both and eventually graded with a higher grade. These sealants (to the right of no-grade-difference) showed declining performance in the field. On the other hand, sealants with a grade lower than the test site grade (negative grade difference) had much lower stiffness than required and were graded accordingly. These sealants (to the left of no-grade-difference) also showed poor performance, possibly due to low stiffness and early overband failure that may have accelerated other types of failures such as adhesive failure. Similar observations, but not as clear as in the rout and seal case, were also observed for the clean and seal treatment (Figure 38b). Sealants with higher grades (positive grade difference) had insufficient cohesive capacity (failing either due to exceeding thresholds for maximum stiffness or minimum extendibility), leading to poor field performance. On the other hand, sealants with lower grade (negative grade difference) could be too soft for the test site. These sealants could suffer from overband wear due to low stiffness.



(a) Rout and seal (b) Clean and seal

Figure 38. Boxplots of the Relationship between Sealants' Grade Difference with Test Site and Their Field Performance

SUMMARY AND CONCLUSIONS

The ASTM standards and specifications currently used to select crack sealant were established based on material properties that are generally empirical and do not measure the fundamental properties of sealants. Also, the specification limits vary from one state to another. These differences create difficulties for crack sealant suppliers because many states with the same environmental conditions specify different limits for the measured properties. These standard tests were also reported to poorly characterize the rheological properties of bituminous-based crack sealants and often fail to predict sealant performance in the field.

Therefore, performance-based guidelines were developed as a systematic procedure to select hot-poured asphalt crack sealants. The work proposed a "Sealant Grade" (SG) system to select hot-poured crack sealant based on environmental conditions. A special effort was made to use the equipment originally developed by SHRP, which was used to measure binder rheological behavior as part of the Performance Grade (PG) system. New tests and corresponding preliminary thresholds for each test were identified to ensure desirable field performance.

However, because the preliminary thresholds were determined based on only limited field data, in this study, an extensive field study was designed to validate and fine-tune the threshold values proposed initially. The scope of this study includes installation of test sites, evaluation of the field performance, and correlation of field performance to lab test results. Finally, new guidelines were developed and validated for full implementation as AASHTO specifications.

Seven test sites were selected in collaboration with participating state departments of transportation in different environmental regions in North America. A wide spectrum of materials was installed in these test sites. Test sites were all wet-freeze climatic zone with some variations in temperature fluctuations. Two commonly used sealing techniques were implemented: (1) rout and seal, and (2) clean and seal. Rout and seal treatments were applied with varying reservoir geometry. Clean and seal treatments were also applied at the same locations to compare the two sealing techniques.

Field inspection of crack sealant performance was conducted annually during the project duration, immediately after crack sealant installation and every winter season during the February-March months. Performance data were routinely collected, including visual distress identification, crack opening displacement, temperature measurements, and sampling for laboratory evaluation. Key observations from the field performance study include:

- Overbanding had a clear and positive impact on the performance of sealants.
- Adhesive failure was the predominant type of failure for rout and seal sections, whereas the clean and seal sections failed either because of complete loss of overband or cohesive failure.
- Overband wear accelerated initiation and progression of adhesive failure.
- The severe temperature drops in winter 2013 and 2014 significantly affected the performance of sealants.
- Most sealants failed (fell below a performance index [PI] threshold of 70%) after 3 years.

Observations (and sampling) from the field installations were used to correlate field to laboratory performance. Important findings from this component of the study include:

- Vacuum oven aging (VOA) is a reasonable method for simulating 2 to 5 years of field aging.
- The current criteria for sealant viscosity appear to ensure sufficient workability during installation at the recommended pouring temperatures.
- A comparison between field performance (PI) and stiffness supports defining two threshold values to avoid sealants that are either too soft or too stiff.
- The worst performing sealants were the ones with low adhesion capacity and high stiffness based on the climatic regions in which they are installed.
- The best performing sealants were the ones with highest adhesion capacity and moderate stiffness.
- For clean and seal treatments, PI decreased as stiffness and/or tensile load increased.
- CSAT showed poor correlation with PI and, therefore, an improved adhesion test was suggested.
- Based on the composite score, for most test sites, a strong or acceptable correlation between field performance and laboratory test parameters was obtained.

- CSBBR stiffness had the strongest correlation followed by adhesion energy and load for rout and seal treatments.
- For clean and seal treatment, CSBBR stiffness had the best score, followed by tensile load and extendibility.

The field performance study supported the field-to-lab correlation exercise, which led to significant modification of one laboratory performance test, the validation of several threshold criteria, and the fine-tuning of several others. Highlights of this facet of the research include:

- A simplified approach for detecting tracking potential using the yield test, which also uses the DSR
- The development and validation of a modified adhesion test
- Two separate low-temperature grading schemes that depend on predominant failure mode of the treatment type
  - The CSBBR and CSDTT methods proposed for clean and fill treatment
  - The CSBBR and CSAT methods proposed for rout and seal treatment
- A revised crack sealant performance grading procedure using the modified tests and new thresholds
  - For the CSBBR test method, a maximum stiffness threshold was reduced from 25 MPa to 15 MPa, defined at 240 sec at 6°C higher than the grading temperature.
  - For the CSBBR test method, a minimum stiffness threshold was introduced and selected at 40 MPa, defined at 1 sec at 6°C higher than the grading temperature.
  - For the CSBBR test method, the average creep ratio (ACR) was kept unchanged (minimum of 0.31).
  - For the CSDTT test method, the extendibility thresholds were kept the same as the provisional standard. However, a secondary threshold was introduced as a maximum tensile load and selected at 25N to avoid the use of less ductile sealants.
  - For CSAT, the minimum adhesion load changed from 50 N to 50 N at -4°C plus 25 N for every 6°C reduction at the test temperature.

Key conclusions from this work include:

- It is important to use the proper grade as a performance criterion. Sealant performance is maximized in the absence of deviation from the proper grade (i.e., when the test site temperature was equivalent to the sealant grade testing temperature). Otherwise, a decline in sealant performance was observed when the deviation increased.
- Rout and seal sections performed much better than the clean and seal sections in this study. Most clean and seal sections failed within 2 years.
- Proper selection of pavements, crack types, and sealant material are critical for the performance of clean and seal sections. As shown with the results obtained from Michigan test deck, clean and seal sections could also perform satisfactorily when the vertical and horizontal crack movements are not expected to be high such as in the case of overlays on jointed concrete pavements.

- VOA is a reasonable aging method for simulating 2 to 5 years of field aging. The stiffness master curves obtained from the CSBBR test for field-aged samples compared well to those determine from laboratory-aged samples.
- The originally established thresholds for the viscosity test ensure sufficient workability at the recommended pouring temperatures.
- Overall, modified CSAT results correlated well with field performance. Sealants with adhesion peak loads less than 20 N had the worst field performance. The results emphasized the significance of adhesive characteristics for avoiding premature failures, regardless of other sealant characteristics.

RECOMMENDATIONS

The effectiveness of a performance-based and systematic process for selection of hot-poured asphalt crack sealants was confirmed through this research. The updated guidelines for crack sealant grade (SG) are presented in Table 26 along with a complete list of AASHTO test methods and specifications revised or developed in the current study. Key observations, findings, and conclusions of this research support the following recommendations:

1. *Pavement owner/agencies should install crack sealants during the fall to avoid unnecessary aging that will take place over the summer.*

2. *Pavement owner/agencies should use the rout and seal treatment technique when possible, particularly when sealing transverse reflective cracking.*

3. *Researchers and AASHTO representatives from the sponsoring members of this pooled fund study (No. TPF-5[225]) should submit the revised tests and guidelines for consideration as new and/or revised AASHTO standards and specifications*.

Table 26. Crack Sealant Performance Grade

Crack Sealant Performance Grade	SG 46							SG 52							SG 58						
	-46	-40	-34	-28	-22	-16	-10	-46	-40	-34	-28	-22	-16	-10	-46	-40	-34	-28	-22	-16	-10
Average 7-day max pavement design temperature, ºC[a]	< 46							< 52							< 58						
Min pavement design temperature, ºC[a]	>-46	>-40	>-34	>-28	>-22	>-16	>-10	>-46	>-40	>-34	>-28	>-22	>-16	>-10	>-46	>-40	>-34	>-28	>-22	>-16	>-10
Original Binder																					
Apparent Viscosity, TP 85 max 3.5 Pa.s min 1.0 Pa.s test temp, ºC	Recommended Installation Temperature																				
Dynamic Shear (MSCR), TP XX-XX flow coeff., min 4.0 kPa.s shear thinning, min 0.7 test temp, ºC	46							52							58						
Dynamic Shear (Yield), TP XX-XX shear stress, min 180 Pa test temp @ 200% strain, ºC	46							52							58						
Vacuum Oven Residue (TP 86)																					
Crack Sealant BBR, TP 87 stiffness at 240 s, max 15 MPa stiffness at 1 s, min 40 MPa avg. creep rate, min 0.31 test temp, ºC	-40	-34	-28	-22	-16	-10	-4	-40	-34	-28	-22	-16	-10	-4	-40	-34	-28	-22	-16	-10	-4
Clean and Seal Treatment																					
Crack Sealant DTT, TP 88 test temp, ºC	-40	-34	-28	-22	-16	-10	-4	-40	-34	-28	-22	-16	-10	-4	-40	-34	-28	-22	-16	-10	-4
extendibility, min (%)	85	85	70	55	40	25	10	85	85	70	55	40	25	10	85	85	70	55	40	25	10
Rout and Seal Treatment																					
Crack Sealant AT, TP 89 test temp, ºC	-40	-34	-28	-22	-16	-10	-4	-40	-34	-28	-22	-16	-10	-4	-40	-34	-28	-22	-16	-10	-4
load, min (N)	200	175	150	125	100	75	50	200	175	150	125	100	75	50	200	175	150	125	100	75	50

Table 26. Crack Sealant Performance Grade (continued)

Crack Sealant Performance Grade	SG 64							SG 70							SG 76						
	-46	-40	-34	-28	-22	-16	-10	-46	-40	-34	-28	-22	-16	-10	-46	-40	-34	-28	-22	-16	-10
Average 7-day max pavement design temperature, ºC[a]	< 64							< 70							< 76						
Min pavement design temperature, ºC[a]	>-46	>-40	>-34	>-28	>-22	>-16	>-10	>-46	>-40	>-34	>-28	>-22	>-16	>-10	>-46	>-40	>-34	>-28	>-22	>-16	>-10
Original Binder																					
Apparent Viscosity, TP 85 max 3.5 Pa.s min 1.0 Pa.s test temp, ºC																					
Dynamic Shear (MSCR), TP XX-XX flow coeff., min 4.0 kPa.s shear thinning, min 0.7 test temp, ºC	64							70							76						
Dynamic Shear (Yield), TP XX-XX shear stress, min 180 Pa test temp @ 200% strain, ºC	64							70							76						
Vacuum Oven Residue (TP 86)																					
Crack Sealant BBR, TP 87 stiffness at 240 s, max 15 MPa stiffness at 1 s, min 40 MPa avg. creep rate, min 0.31 test temp, ºC	-40	-34	-28	-22	-16	-10	-4	-40	-34	-28	-22	-16	-10	-4	-40	-34	-28	-22	-16	-10	-4
Clean and Seal Treatment																					
Crack Sealant DTT, TP 88 test temp, ºC	-40	-34	-28	-22	-16	-10	-4	-40	-34	-28	-22	-16	-10	-4	-40	-34	-28	-22	-16	-10	-4
extendibility, min (%)	85	85	70	55	40	25	10	85	85	70	55	40	25	10	85	85	70	55	40	25	10
Rout and Seal Treatment																					
Crack Sealant AT, TP 89 test temp, ºC	-40	-34	-28	-22	-16	-10	-4	-40	-34	-28	-22	-16	-10	-4	-40	-34	-28	-22	-16	-10	-4
load, min (N)	200	175	150	125	100	75	50	200	175	150	125	100	75	50	200	175	150	125	100	75	50

Table 26. Crack Sealant Performance Grade (continued)

Crack Sealant Performance Grade	SG 82						
	-46	-40	-34	-28	-22	-16	-10
Average 7-day max pavement design temperature, ºC[a]	< 82						
Min pavement design temperature, ºC[a]	>-46	>-40	>-34	>-28	>-22	>-16	>-10
Original Binder							
Apparent Viscosity, TP 85 max 3.5 Pa.s min 1.0 Pa.s test temp, ºC							
Dynamic Shear (MSCR), TP XX-XX flow coeff., min 4.0 kPa.s shear thinning, min 0.7 test temp, ºC	82						
Dynamic Shear (Yield), TP XX-XX shear stress, min 180 Pa test temp @ 200% strain, ºC	82						
Vacuum Oven Residue (TP 86)							
Crack Sealant BBR, TP 87 stiffness at 240 s, max 15 MPa stiffness at 1 s, min 40 MPa avg. creep rate, min 0.31 test temp, ºC	-40	-34	-28	-22	-16	-10	-4
Clean and Seal Treatment							
Crack Sealant DTT, TP 88 test temp, ºC	-40	-34	-28	-22	-16	-10	-4
extendibility, min (%)	85	85	70	55	40	25	10
Rout and Seal Treatment							
Crack Sealant AT, TP 89 test temp, ºC	-40	-34	-28	-22	-16	-10	-4
load, min (N)	200	175	150	125	100	75	50

The AASHTO test specifications should be used in determination or verification of hot-poured asphalt crack sealant grade. The following AASHTO test method and specifications were revised or developed during the project period:

- AASHTO MP-25, Performance-Graded Hot-Poured Asphalt Crack Sealant (under review)
- AASHTO PP xx, Grading or Verifying the Sealant Grade (SG) of a Hot-Poured Asphalt Crack Sealants (under review)
- AASHTO TP 85, Apparent Viscosity of Hot-Poured Asphalt Crack Sealant Using Rotational Viscometer
- AASHTO TP 86, Accelerated Aging of Hot-Poured Asphalt Crack Sealants Using a Vacuum Oven
- AASHTO TP 87, Measure Low-Temperature Flexural Creep Stiffness of Hot-Poured Asphalt Crack Sealants by BBR
- AASHTO TP 88, Evaluation of the Low-Temperature Tensile Property of Hot-Poured Asphalt Crack Sealants by Direct Tension Test
- AASHTO TP 89, Measuring Adhesion of Hot-Poured Asphalt Crack Sealant Using Direct Adhesion Tester
- AASHTO TP 90, Measuring Interfacial Fracture Energy of Hot-Poured Crack Sealant Using a Blister Test
- AASHTO TP xx, Evaluation of the Tracking Resistance of Hot-Poured Asphalt Crack Sealants by Dynamic Shear Rheometer (DSR) (under review)
- ASTM D 5167, Standard Practice for Melting of Hot-Applied Joint and Crack Sealant and Filler for Evaluation

COSTS AND BENEFITS ASSESSMENT

A survey on pavement preventive maintenance programs from 18 transportation agencies in North America shows significant investments in these programs (Al-Qadi et al., 2009). Hence, if sealing cracks could prove to be a cost-effective technique, life-cycle savings could be realized. Life-cycle cost analysis was performed to evaluate life-cycle benefits through sealing treatments. The standard procedures with a 30-year analysis period and the following assumptions were followed (Hein and Rao, 2010):

- Pavement lasts 8.5 years without any application of treatment. Proper crack sealing application extends the pavement life by 2 years.
- The initial construction is assumed to be for a 300 mm full-depth asphalt. This includes 75 mm of polymerized hot mixed asphalt (HMA), 125 mm of binder HMA, and 50 mm of stone mastic asphalt with prime coat.
- Initial pavement condition index is 93. Overlay application restores the performance to its original value. Overlays are 100 mm of HMA, and overlay performance is considered identical to performance upon initial construction.
- Cracks are occurring on an average distance of 6.1 m. Rout and seal is used. All sealants are assumed to cost an average value. The total costs are assumed to be indifferent to the

year of application (e.g., the cost for sealing in the second year is assumed to be the same as that for a sixth year).

- Other costs to initial construction, overlays construction, and sealing applications are not considered, including delays and traffic issues related to pavement maintenance and preservation.

Different crack-sealing cycles were used to create three cost analyses that sought the minimum extension in pavement life necessary to justify sealing. These scenarios are as follows:

- Scenario 1: Sealant application every 4 years
- Scenario 2: Sealant application at third, sixth, and eighth years
- Scenario 3: Sealant application every 2 years

Table 27 shows the results for the three scenarios. Scenario 1 represents excellent sealant performance where the sealant lasts for 4 years. Scenario 2 shows good sealant performance where the sealant lasts for 3 years. The fair sealant performance presented in Scenario 3 indicates that the sealant lasts for 2 years only. It was shown that even an incremental improvement in pavement life (such as less than only 1 year) would be sufficient for sealing to be cost-effective. It also shows the importance of selecting a proper sealant for each situation. The fewer the number of sealant applications, the more cost effective the sealing approach becomes and, conversely, the more frequent the number of sealant treatments, the greater the cost.

Table 27. Pavement Life Extension in Number of Years for Sealing Application to Be Cost-Effective

Scenario	Scenario 1 (excellent sealant performance)	Scenario 2 (good sealant performance)	Scenario 3 (fair sealant performance)
Extending pavement life (years)	0.16	0.25	0.34

ACKNOWLEDGMENTS

This research is sponsored by the Federal Highway Administration's Pooled Fund Study TPF5 (225). The contribution of the participating states, industry, and provinces is acknowledged. The authors thank Kevin McGhee (VDOT), Bill Bailey (VDOT), Imran Bashir (Ministry of Transportation Ontario), Andy Bennett (MDOT), Paulette Hanna (WisDOT), Beran Black (NHDOT), Jim McGraw (MNDOT), and Eddie Johnson (MNDOT). The contents of this report reflect the view of the authors, who are responsible for the facts and the accuracy of the data presented herein. The content does not necessarily reflect the official views or policies of the pool-fund participating departments of transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. The authors also thank the research engineers of the Illinois Center for Transportation for their help and assistance in the pooled fund study.

REFERENCES

American Association of State Highway and Transportation Officials (AASHTO), Final Report of Field and Laboratory Evaluation of Hot-Mix Crack Sealing Materials, Publication NTPEP Report 16002.3, AASHTO, Washington, DC, June 2009.

Al-Qadi, I. L., Fini, E., Elseifi, M., Masson, J-F, and McGhee, K. (2006). Procedure for Viscosity Determination of Hot-Poured Bituminous Sealants, *Transportation Research Record: Journal of the Transportation Research Board*, No. 1958, pp. 74-81.

Al-Qadi, I., Loulizi, A., Aref, S., Masson, J-F, and McGhee, K. K. (2005). Modification of Bending Beam Rheometer Specimen for Low-temperature Evaluation of Bituminous Crack Sealants, *Transportation Research Record: Journal of the Transportation Research Board*, No. 1933, pp. 97-106.

Al-Qadi, I. L., Masson, J-F, Dessouky, S., Collins, P., Yang, S-H, Bundalo-Perc, S., Fini, E., Elseifi, M., and McGhee, K. K. (2005). *Development of Performance Guidelines for Selection of Hot-Poured Crack Sealants*, Publication Interim Report No. B5508-7, National Research Council of Canada, September.

Al-Qadi, I. L., Masson, J-F, Loulizi, A., Collins, P., Woods, J. R., Bundalo-Perc, S., and McGhee, K. K. (2004). *Long-Term Accelerated Aging and Low Temperature BBR Testing of Sealants*, Publication Interim Report No. B5508-7, National Research Council of Canada.

Al-Qadi, I. L., Masson, J-F, Yang, S-H, and Fini, E. (2008). *Towards Performance-Based Selection Guidelines for Roadway Crack Sealant*, Publication Report No. NRCC-50835, National Research Council of Canada, August.

Al-Qadi, I. L, Yang, S-H, Dessouky, S., and Masson, J-F. (2007). Low Temperature Characterization of Hot-Poured Crack Sealant Using Modified SHRP Direct Tensile Tester, *Transportation Research Record: Journal of the Transportation Research Board*, No. 1991, pp. 109-118.

Al-Qadi, I. L, Yang, S-H., Dessouky, S., Masson, J-F, Loulizi, A., and Elseifi, M. (2007). Development of Crack Sealant Bending Beam Rheometer (CSBBR) Testing to Characterize Hot-Poured Bituminous Crack Sealant at Low Temperature, *Journal of AAPT*, Vol. 76, pp. 85-122.

Al-Qadi, I., Yang, S-H, Elseifi, M., Masson, J-F, and McGhee, K. (2006). *Specifications of Bituminous-Based Crack Sealants Using Modified Bending Beam Rheometer*, TRB Paper No. 06-1882. The 85th Annual Meeting of the Transportation Research Board, National Research Council, Washington, DC.

Al-Qadi, I., Masson, J.-F., Fini, E., Yang, S.-H., & McGhee, K. K. (2009). *Development of Performance-Based Guidelines for Selection of Bituminous-Based Hot-Poured Pavement Crack Sealant: An Executive Summary Report*. Illinois Center for Transportation, Springfield.

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

ASTM D6690 (2006). *Standard Specification for Joint and Crack Sealants, Hot Applied, for Concrete and Asphalt Pavements*, American Society for Testing and Materials, Philadelphia, PA.

ASTM D5329 (2004). *Standard Test Methods for Sealants and Fillers, Hot-Applied, for Joints and Cracks in Asphaltic and Portland Cement Concrete Pavements,* American Society for Testing and Materials, Philadelphia, PA.

ASTM C670 (2003). *Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials*, American Society for Testing and Materials, Philadelphia, PA.

Belangie, M. C., and Anderson, D. I. (1985). *Crack Sealing Methods and Materials for Flexible Pavements*, Publication FHWA-UT-85-1, Utah Department of Transportation, Salt Lake City.

Chong, G. J., and Phang, W. A. (1987). Consequences of Deferred Maintenance Treatment on Transverse Cracks in Cold Regions, *Proceedings of Paving in Cold Areas Mini-Workshop,* Ottawa, Ontario, Canada, pp. 638-686.

Chong, G. J., and Phang, W. A. (1987). *Improved Preventive Maintenance: Sealing Cracks in Flexible Pavements in Cold Regions*, Publication PAV-87-01, Ontario Ministry of Transportation, Downsview, Ontario, Canada.

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

Collins, P., Veitch, M., Masson, J-F, and Al-Qadi, I. (2008). Deformation and Tracking of Bituminous Sealants in Summer Temperatures: Pseudo-Field Behavior, *International Journal of Pavement Engineering,* Volume 9, pp. 1-8.

Cuelho, E., Johnson, D. R., and Freeman, R. B. (2002). *Cost-Effectiveness of Crack Sealing Materials and Techniques for Asphalt Pavements*, Publication FHWA/MT-02-002/8127, Montana Department of Transportation, Helena.

Cuelho, E., Ganeshan, S. K., Johnson, D. R., Freeman, R. B., and Schillings, P. L. (2003). *Relative Performance of Crack Sealing Materials and Techniques for Asphalt Pavements*, Third International Symposium on Maintenance and Rehabilitation of Pavements and Technological Control, Guimarães, Portugal, pp. 327–337.

Cuelho, E., and Freeman, R. B. (2004). *Cost-Effectiveness of Crack Sealing Materials and Techniques for Asphalt Pavements*. Montana Department of Transportation, Helena.

Elseifi, M., Dessouky, S., Al-Qadi, I. L., and Yang, S-H (2006). A Viscoelastic Model to Describe the Mechanical Response of Bituminous Sealants at Low Temperature, *Transportation Research Record: Journal of the Transportation Research Board*, No. 1958, pp. 82-89.

Fang, C., Galal, K. A., Ward, D. R., Haddock, J. E., and Kuczek, T. (2003). *Cost-Effectiveness of Joint and Crack Sealing,* Presented at the 82nd Annual Meeting of the Transportation Research Board, Washington, DC.

Fang, C., Haddock, J., Galal, K., and Ward, D. (2003). *Initial Study for Cost-Effectiveness of Joint/Crack Sealing*. Indiana Department of Transportation, Indianapolis.

Fini, E., Al-Qadi, I. L., and Dessouky, S. H. (2006). *Adhesion of Hot-Poured Crack Sealant to Aggregate,* The 85th Annual Meeting of the Transportation Research Board, National Research Council, Washington, DC.

Fini, E., Al-Qadi, I. L., Masson, J-F, & McGhee, K. K. (2008). Interfacial Fracture Energy: An Indicator of the Adhesion of Bituminous Materials, *Journal of AAPT*, Vol. 77, pp. 827-850.

Gibson, N., Qi, X., Shenoy, A., Al-Khateeb, G., Kutay, M. E., Andriescu, A. and Harman, T. (2012). *Performance testing for Superpave and structural validation*, Publication FHWA-HRT-11-045. Washington, DC: Federal Highway Administration Research and Technology.

Hein, D. K., and Rao, S. (2010). Rational Procedures for Evaluating the Effectiveness of Pavement Preservation Treatments. *Compendium of Papers from the First International Conference on Pavement Preservation*, pp. 117-130.

Masson, J. F., Boudreau, B., and Girard, C. (2003). Guidelines for Sealing and Filling Cracks in Asphalt Concrete Pavement: A Best Practice, National Guide to Sustainable Municipal Infrastructure, National Research Council Canada, Canada.

Masson, J-F, Collins, P., Perraton, D., and Al-Qadi, I. L. (2007). Rapid Assessment of the Tracking Resistance of Bituminous Crack Sealants, *Canadian Journal of Civil Engineering,* Vol. 34, pp. 126-131.

Masson, J.-F. (2000). Bituminous Sealants for Pavement Joints and Cracks: Building the Basis for a Performance-Based Specification, In *Durability of Building and Construction Sealants*, A. Wolf, Ed., RILEM, Paris, pp. 315-328.

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.

Ozer, H., Solanki, P., Yousefi, S. S., and Al-Qadi, I. L. (2014). Field Validation of Laboratory-Predicted Low-Temperature Performance of Hot-Poured Crack Sealants. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2431, pp. 57-66.

Ozer, H, Yousefi, S. S., Al-Qadi, I. L., and Elizalde, G. (2015). Field Aging and Development of Aging Model for Hot-Poured Crack Sealants. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2481, pp. 90-99.

Panea, 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, pp. 86-94.

Panea, J. (1990). *Field Evaluation of Rout and Seal Crack Treatment in Flexible Pavement*, Publication PAV-90-03, Ministry of Transportation of Ontario, Downsview, Ontario, Canada.

Penn, L. S., and Defex, E. (2002). Relation between Work of Adhesion and Work of Fracture for Simple Interfaces, *Journal of Materials Science*, Vol. 37, pp. 505-513.

Peshkin, D., Smith, K. L., Wolters, A., Krstulovich, J., Moulthrop, J., and Alvarado, C. (2011). *Guidelines for the Preservation of High-Traffic-Volume Roadways*. Transportation Research Board, Washington, DC.

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

Smith, K. L., and Romine, A. R. (1993). *Innovative Materials Development and Testing Volume 3: Treatment of Cracks in Asphalt Concrete-Surfaced Pavements*, Publication SHRP-H-354. Strategic Highway Research Program, National Research Council, Washington, DC.

Smith, K. L., and Romine, A. R. (1999). *LTPP Pavement Maintenance Materials: SHRP Crack Treatment Experiment*, Publication FHWA-RD-99-143, FHWA, U.S. Department of Transportation, Washington, DC.

Solanki, P., Ozer, H., Yousefi, S. S., and Al-Qadi, I. L. (2014). Effect of Installation Parameters on Performance of Hot-Poured Crack Sealants. *Proceeding of T&DI Congress*, Orlando, FL, pp. 142-152.

Wang, Y., Wang, G., and Mastin, N. (2012). Costs and Effectiveness of Flexible Pavement Treatments: Experience and Evidence. *Journal of Performance of Constructed Facilities*, Vol. 26, Issue 4, pp. 516–525.

Ward, D. R. (2001). *Evaluation of the Implementation of Hot-Pour Sealants and Equipment for Crack Sealing in Indiana*, Publication FHWA/IN/JTRP-2000/27, FHWA, U.S. Department of Transportation, Washington, DC.

Yang, S-H, and Al-Qadi, I. (2008). A Modified Direct Tension Test (DTT) for Bituminous Crack Sealant Characterization at Low Temperature. *Journal of AAPT*, Vol. 77, pp. 107-142.

Yousefi, S. S., Ozer, H., Hafeez, I., and Al-Qadi, I. L. (2016). *Field and Laboratory Low Temperature Performance of Hot-Poured Crack Sealants in Michigan*. Presented at 95th Annual Meeting of the Transportation Research Board, Washington, DC.

Yousefi, S. S., Ozer, H., and Al-Qadi, I. L. (2016). *Identification of Low Temperature Stiffness Thresholds for Hot-Poured Sealants Using the Crack Sealant Bending Beam Rheometer Test Method*. Presented at 95th Annual Meeting of the Transportation Research Board, Washington, DC.