Technical Report Documentation Page

1. FHWA/TX-06/0-4061-3	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Performance Comparison of Hot Rubber Crack Sealants to Emulsified Asphalt Crack Sealants		5. Report Date May 2006
7. Author(s) Yetkin Yildirim, Armagan Korkmaz, and Jorge Prozzi		6. Performing Organization Code 8. Performing Organization Report No. 0-4061-3
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, TX 78705-2650		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 0-4061
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, Texas 78763-5080		13. Type of Report and Period Covered Technical Report (9/00 – 9/04) 14. Sponsoring Agency Code
15. Supplementary Notes Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.		
16. Abstract		
17. Key Words Hot Poured Crack Sealants, Cold Poured Crack Sealants, Emulsified Crack Sealants, Asphalt Pavements	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161; www.ntis.gov.	
19. Security Classif. (of report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 64 / 22. Price

16. Abstract

This is the final report from the Center for Transportation Research on Project 4061. It presents the results, findings, conclusions, and recommendations based on the surveys, lab tests, and information collected on test sections for the 4-year study. Sealing and filling cracks has always been an important consideration in pavement maintenance. Hot rubber asphalt has been the most commonly used material for this purpose, providing good performance in most cases. Some Texas Department of Transportation (TxDOT) districts have been using cold pour asphalt emulsion crack sealants because of the ease of use. However, cold pour crack sealant requires longer setting and curing time, especially in areas of high humidity. The performance history of these cold sealants is not known or not well documented in comparison to the performance of hot pour crack sealants. Furthermore, the cost associated with the use of this material versus hot pour rubber asphalt is not well documented or determined. The intent of this research project is to compare the cost-effectiveness, performance, and life-cycle costs for hot pour rubber asphalt crack sealant and cold pour asphalt emulsion crack sealant. The comparison includes seven different crack and joint sealants: three cold pour and four hot pour. Eight different roads in five districts were selected for comparison of the sealants, for a total of thirty-three different test sections. The survey and field study results indicate that hot pour sealants performed better than cold pour sealants. In addition, hot pour sealants had lower average annual cost values than cold pour sealants. Modifications to the specifications for crack sealants currently used at TxDOT were suggested.

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Performance Comparison of Hot Rubber Crack Sealants to Emulsified Asphalt Crack Sealants

Yetkin Yildirim, Ph.D., P.E.
Armagan Korkmaz
Jorge Prozzi, Ph.D.

CTR Technical Report:	0-4061-3
Report Date:	May 2006
Project:	0-4061
Project Title:	Comparison of Hot Rubber Crack Sealants to Emulsified Asphalt Crack Sealants
Sponsoring Agency:	Texas Department of Transportation
Performing Agency:	Center for Transportation Research at The University of Texas at Austin

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

Center for Transportation Research
The University of Texas at Austin
3208 Red River
Austin, TX 78705

www.utexas.edu/research/ctr

Preface

This is the final report from the Center for Transportation Research on Project 4061. It presents the results, findings, conclusions, and recommendations based on the surveys, lab tests, and information collected on test sections for the 4-year study. The surveys were conducted to gather information on crack sealing practices from different states and Texas Department of Transportation (TxDOT) districts, while the study compared the performance of hot pour and cold pour sealants in the field.

Acknowledgments

This project has been initiated and sponsored by TxDOT. The financial support of TxDOT is greatly appreciated. The authors would like to thank TxDOT Project Director John Bohuslav for his guidance. Special thanks are extended to Darren Hazlett, Jerry Peterson, and Larry Miller of TxDOT for their great assistance in conducting the laboratory tests. The assistance of the participating district maintenance personnel through the advisory committee, as well as other district personnel in crack sealing the test sections, is greatly appreciated. We are also grateful to Joe Rohmer and his crew for their perseverance in carrying forward and conducting the sealing operations.

Disclaimers

Dr. Yetkin Yildirim, P.E. (Texas No. 92787)
Dr. Jorge Prozzi

Table of Contents

List of Tables

List of Figures

Chapter 1. Introduction

1.1. Summary

An important element of pavement maintenance practices is the sealing and filling of cracks. Hot pour materials are the most commonly used material, providing good performance in most cases. Some Texas Department of Transportation (TxDOT) districts have looked into the use of cold pour asphalt emulsion crack sealants. Cold pour crack sealants require longer setting and curing times, especially in areas of high humidity. In addition, the performance history of these cold pour sealants is not known nor well documented in comparison to the performance of hot rubber crack sealants. The costs associated with the use of this material versus hot rubber asphalt are also not well documented or determined.

This research project is intended to compare the cost-effectiveness, performance, and life-cycle costs for hot pour rubber asphalt crack sealant and cold pour asphalt emulsion crack sealant. The comparison includes seven different crack and joint sealants: three cold pour and four hot pour rubber sealants. Eight different roads in five districts were selected for the comparison of the sealants. Sealants were applied to these roads between January and April 2001. A total of thirty-three different test sections were obtained through this operation. The crack-sealed sections in all five districts were visited and monitored at regular intervals throughout the project duration.

The surveys and field study indicate that hot pour rubber sealants performed better than cold pour sealants. In the test sections, hot pour sealants performed better over time than cold pour sealants. The cost analyses showed that the overall average *average annual cost* (AAC) for cold pour materials is \$0.107/ft with a standard deviation of 0.06, and for hot pour materials, the average AAC is \$0.045/ft with a standard deviation of 0.042. Modifications to the specifications for crack sealants currently used at TxDOT were suggested. These modifications include characterizing the sealants by using bending beam rheometer (BBR) and dynamic shear rheometer (DSR) tests, in addition to what is available in the specifications.

1.2. Background

Crack treatment, including crack sealing, crack filling, and crack repair, is one of the most common maintenance activities performed on bituminous pavements by local governmental agencies. Crack sealing is the method of placing material in a crack to create a watertight barrier. Transverse and longitudinal crack sealing is performed frequently in order to extend pavement life by preventing or substantially reducing the infiltration of water into the pavement structure. Generally, rubberized materials are considered to be effective crack sealants because of their ductile properties.

Sealing cracks in asphalt pavements have long been regarded as an annual preventive maintenance procedure. With limited maintenance budgets and increasing labor and material costs, some means of reducing the life-cycle cost of crack seals is required. Polymer modified asphalt crack sealer materials, as defined by American Society for

Testing and Materials (ASTM) D3405, have demonstrated the potential to deliver 5 or more years of service life.

Highway agencies use different materials and methods to treat cracks in asphalt concrete pavements. Some of these treatments are inherently better than others; however, the relative effectiveness of a treatment often depends on the situations in or conditions under which they are used.

For many years, TxDOT and other state highway agencies have been using hot rubber asphalt crack sealants. While this material generally has performed well, it is somewhat hazardous to apply. Hot rubber asphalt crack sealant must be heated to approximately 350 °F (177 °C) before it is applied to the pavement surface. This heating can take significant time before work can begin. Burns and skin damage are safety concerns with hot rubber if a hose or nozzle blows off and any material accidentally lands on workers, inspectors, or the traveling public during this process. In addition, if the material does not cure properly or if it does not adhere correctly to the pavement, it can be picked up by vehicle tires and may become very difficult to remove. Normally, the hot rubber crack sealant provides an elastic seal that will adhere to the pavement and contract/expand very well with movement of the pavement. However, when excessive sealant is applied on the surface of cracks, in some cases the sealant does not perform as intended and can cause other maintenance problems.

In some TxDOT districts, use of cold pour asphalt emulsion crack sealant has replaced use of hot rubber asphalt. Cold pour asphalt emulsion crack sealant is typically applied at ambient temperature, which makes its use much safer for workers, inspectors, and the traveling public. However, it may require longer setting and curing times, making it more difficult to use in high-traffic areas. High humidity conditions can also slow the cure time for cold pour crack sealants. Freezing weather conditions immediately following application of the cold pour sealant can also adversely affect its effectiveness. Much less setup time is required for cold pour work because no heating time is needed. Because the cold pour sealant has very low viscosity, it can penetrate and fill cracks more easily than the hot rubber. However, little is known about the long-term performance of cold pour crack sealant.

Because hot rubber sealant is provided in solid blocks, it is generally measured and paid for by the pound. On the other hand, cold pour sealant is provided in liquid form in drums. Generally, it is measured and paid for by the gallon. Because of the extreme difference in the characteristics of each material, there can be wide variations between pounds of hot rubber sealant and gallons of cold pour sealant to seal the same crack. Thus, it is often quite difficult to determine a unit cost comparison (such as cost per foot of crack sealed) for the work completed with each type of material. Because there is little or no research available on the cost for use of each material on the same road under the same conditions and in the same types of cracks, the cost per foot of crack sealed typically is not known. At TxDOT, there has been no formal follow-up research study on performance differences between hot rubber sealant and cold pour sealant at 1 year, 2 years, or 3 years after the material is applied. Although it may be somewhat simple to determine the initial cost of installation for each type of material, it is more important to determine the general life-cycle cost for each type of material used.

Finally, if maintenance engineers and maintenance managers can determine the life of a crack seal, they can more easily determine when a seal coat or overlay project should be applied.

1.3. Past Research and Experience

Although a comparison of hot pour and cold pour sealants has not been specifically studied before now, some information on sealant performance is available, dating back to 1992. Smith and Romine (1) produced an asphalt pavement repair manual of practice based on a comprehensive study of crack treatment methods. This study included installing thirty-one unique crack treatments (i.e., combinations of sealant/filler materials and installation method) at five different test sites, 7-year performance monitoring of the various crack treatments, and laboratory testing of experimental sealant/filler materials.

Masson and Lacasse (2) conducted a study to measure the adhesion strength of bituminous crack sealant to dry asphalt concrete (AC) and assess the effect of the hot-air lance (HAL) on adhesion. The results showed that sealant adhesion and failure mechanisms were governed by the sealant source, the type of aggregate in the AC mix, and the heat treatment on the rout prior to pouring the sealant. HAL does not oxidize the binder, but it may cause embrittlement by raising the asphaltene content of the binder. Normal heat treatment has little effect on sealant adhesion to dry AC, but overheating can cause a 50 percent reduction in adhesion strength and lead to premature sealant failure. To retain the possible benefits of the HAL in sealing damp cracks and to prevent overheating, the HAL should be operated at reduced temperatures.

Bruggeman et al. (3) studied the performance of some pavements sealed with polymerized emulsion crack sealants in Minnesota. They observed somewhat higher failure rates than expected. The following types of failure were noted: the elasticity limits of the material were exceeded; the sealant pulled away from the edges; routing was inadequate; and the material was unsuitable for the extreme temperature variations experienced in northern Minnesota. The solutions were to: specify a proven sealant; change the routing width and depth requirements to provide sufficient reservoir for the sealant; increase the training provided to county employees; set weather condition limits; and develop a new specification with special provisions to address the conditions that northern Minnesota experiences. These conditions, such as extreme variations in seasonal temperatures, heavy clay soils, and high water tables, cause the subsoils and base and pavement surface to move more than those of highways farther south.

Ward (4) reports studying twelve crack sealants evaluated over 40 months in Indiana. Only one, a crumb rubber product, had an overall "group" success rate above 70 percent, as defined by the American Association of State Highway and Transportation Officials (AASHTO). The best-performing sealant/treatment combination was a single component polymer placed in a rout cleaned with compressed air, which had a success rate of 81.4 percent after 40 months. The current Indiana Department of Transportation (INDOT) asphaltic emulsion sealant had an overall group success rate of 6.5 percent after 40 months. All asphaltic emulsion sealant treatment combinations reached near total failure after 2 years. The field process currently used by INDOT (straight squeegee and compressed air cleaning) had a success rate of 4.9 percent after one and a half years. The functional life of the asphaltic emulsion as placed by INDOT maintenance crews is believed to be significantly less than 1 year. Several of the "better" sealants evaluated (+70 percent success rate) are projected to have functional lives of 4 to 6 years. According to Ward, this is supported by the experience of other departments of transportation.

Chichak (5) reports that the Alberta Department of Transportation has been testing ASTM D3405 materials on a limited scale since the early 1980s. Wide-scale testing of this class of sealer took place throughout Alberta (Canada) in 1990, which was monitored by the Research and Development Branch. It was concluded that properly installed seals can deliver a 5-year service life and, in spite of the higher material and installation cost, will be cost-effective compared to traditional materials and methods after 3 years of service.

Eaton and Ashcraft reported a state-of-the-art survey of flexible pavement crack sealing procedures in the United States (6). The survey included all 50 states and was conducted in September 1990. The results were tabulated and a summary report prepared, which identified the need for a trade organization to develop uniform specifications and terminology, and to promote proper equipment, methodology, materials, training, and education in the pavement crack sealing industry.

1.4. Objectives of Presented Work

The comparison of four different types of sealants in terms of performance, cost-effectiveness, and life-cycle cost was the main objective of this study. These four types of sealants are:

- Hot rubber asphalt crack sealants
- Hot rubber asphalt joint sealants
- Cold pour asphalt emulsion crack sealants
- Cold pour asphalt emulsion joint sealants

Crack sealants are those used to seal the cracks generated in asphalt pavements. Joint sealants refer to sealants used to seal the joints between concrete slabs, joints between adjacent layers of asphalt concrete, or joints between asphalt and concrete pavements.

Chapter 2. Survey on Crack Sealing Techniques and Materials

A survey was distributed to the Departments of Transportation of nine U.S. states (Alaska, Arizona, Maryland, New Jersey, New York, North Carolina, Oregon, Pennsylvania, and Utah) and to twenty-five districts in Texas, of which twenty-one responded. All of the states used hot pour sealants, and five of them also used cold pour sealants. Ten questions were posed in the survey; each was answered in the form of a ranking such as poor, fair, good, and excellent. According to the state and district surveys, hot pour sealants perform well in all areas except for resistance to flushing and bleeding, while cold pour sealants were regarded as poor in most cases. The effective service life of cold pour sealants was never greater than 3 years, while the effective service life of hot pour sealants was as long as 5 years. Both district and state survey results clearly showed that hot pour sealants performed better than cold pour sealants. Detailed information about this survey can be found in Report 4061-1.

Chapter 3. Materials Used in the Test Sections

Through coordination with the Texas Department of Transportation (TxDOT), eight asphalt pavement roads in five different districts were selected for the application of different sealants. Both cold pour and hot pour sealants were applied to the roads. Applying both types of sealants to the cracks of the same pavement was intended to make the results of the analysis more reliable because influencing factors such as traffic, climate, and pavement type and condition remain the same for both types of sealants.

Table 3.1 and Table 3.2 show the districts and sealants used for comparison, differentiating between the presence and absence of subsequent seal coats or overlays. As presented in the tables, a total of thirty-three test sections were crack sealed during the period of January to April 2001. Table 3.1 presents those test sections that were not covered (overlaid or seal coated) for at least 3 years after they were crack sealed, referred to as *non-covered sections*. The purpose of regular visits was to evaluate the treatment effectiveness of the sealants. Table 3.2 presents those test sections that were covered with hot mix asphalt concrete or a chip seal during the summers of 2001 or 2002, referred to as *covered sections*. The purpose of these covered test sections was to evaluate the tendency for certain crack sealants to bleed or flush through the overlaying hot mix asphalt concrete or chip seal.

Table 3.1. Crack-Sealed Highway Non-Covered Test Sections

Sealant	Cold Pour C1	Cold Pour C2	Cold Pour C3	Hot Pour H1	Hot Pour H2	Hot Pour H3	Hot Pour H4
	Crack Seal	Crack Seal	Joint Seal	Crack Seal	Crack Seal	Crack Seal	Joint Seal
TxDOT Spec TxDOT District	Item 3127	Item 3127	DMS-6310, Class 9 (Joint Seal)	GSD 745-80-25, Type I, Class A	GSD 745-80-25, Type III, Class B	GSD 745-80-25, Type I, Class A	DMS-6310, Class 3 (Joint Seal)
Atlanta	√	√	√	√	√		
El Paso	√	√			√	√	
Lufkin		√	√	√			√
Amarillo	√		√	√		√	√
San Antonio	√	√	√	√	√	√	√
Total	4	4	4	4	3	3	3

Table 3.2. Crack-Sealed Highway Covered Test Sections

Sealant	Cold Pour C1	Cold Pour C2	Cold Pour C3	Hot Pour H1	Hot Pour H2	Hot Pour H3	Hot Pour H4
	Crack Seal	Crack Seal	Joint Seal	Crack Seal	Crack Seal	Crack Seal	Joint Seal
TxDOT Spec TxDOT District	Item 3127	Item 3127	DMS-6310, Class 9 (Joint Seal)	GSD 745-80-25, Type I, Class A	GSD 745-80-25, Type III, Class B	GSD 745-80-25, Type I, Class A	DMS-6310, Class 3 (Joint Seal)
Atlanta*		√		√			
El Paso							
Lufkin†	√	√		√		√	
Amarillo*	√					√	
San Antonio							
Total	2	2	0	2	0	2	0

*Overlays and chip seals were applied in summer 2001 in Atlanta and Amarillo.
† Overlays and chip seals were applied in summer 2002 in Lufkin.

In labeling the sealants in Tables 3.1 and 3.2, numbers (1, 2, etc.) are used simply to distinguish between different brands of sealants. Letters C and H in the label refer to the type of sealant. Cold pour sealants (those labeled C in the tables) are in liquid form and are applied at ambient temperature. Hot pour rubber sealants (those labeled H in the tables) are available in the form of solid blocks and are applied at temperatures exceeding 380 °F.

Crack sealants and joint sealants of each type, hot pour and cold pour, were used in this study. Crack sealants are used to fill pavement cracks, whereas joint sealants are generally used to seal concrete pavement joints. Two different cold pour crack sealants (C1 and C2) and one cold pour joint sealant (C3) were applied. Crack sealants C1 and C2 met TxDOT requirements for Item 3127 specifications. The joint seal C3 satisfied TxDOT requirements of DMS-6310, Class 9 specifications. Three hot pour crack sealants (H1, H2, and H3), and one hot pour joint sealant (H4) were used. Crack sealants H1 and H3 satisfied TxDOT's GSD Spec. 745-80-25, Class A requirements, and crack sealant H2 satisfied GSD Spec. 745-80-25, Class B requirements. Joint sealant H4 met DMS-6310, Class 3 specification requirements. Laboratory test results of the sealing materials used in this study are depicted in Appendix A. Specifications for GSD 745-80-25, Item 3127 and DMS-6310 are located in Appendix B.

Chapter 4. Performance Evaluation

Crack sealants on thirty-three sections of eight different roads were monitored for performance. The test sections were divided into two groups. The first group, the non-covered sections, included twenty-five test sections that were not overlaid or seal coated within 3 years of sealant application. The second group, the covered sections, included eight test sections that were overlaid or seal coated during summer 2001 or summer 2002.

4.1. Frequency of Inspection

4.1.1. Non-covered Test Sections

In order to monitor the performance of the different crack sealants, the test sections were visited for visual inspection regularly to chart the rate of failure, making a comparison of performance more meaningful. The performance monitoring in this study included investigative visits to test sections once every winter (i.e., Jan–Feb) and once every summer (i.e., July–Aug) for 3 years. Report 4061-1 and 4061-2 presented performance data collected previously. This final report presents the performance of the sealants throughout the project’s duration.

4.1.2. Covered Test Sections

After they were crack sealed, eight of the covered test sections were seal coated during the summers 2001 and 2002. These test sections were evaluated to determine their tendency to exhibit asphalt bleeding through the subsequent seal coat. The amount of bleeding after the placement of a chip seal was recorded. In order to monitor their performance, visual inspections of the test sections were performed regularly. The performance monitoring included investigative visits to test sections once every winter (i.e., Jan–Feb) and once every summer (i.e., July–Aug) for 3 years.

4.2. Performance Three to Four Months after Construction

4.2.1. Non-covered Sections

Three to 4 months after construction, the performance of the twenty-five non-covered sections was inspected. Test sections were visually monitored for four types of failure, including the opening of previously sealed cracks, the loss of seal in previously sealed cracks, the settlement and bleeding of sealants, and the pullout of material.

As defined in AASHTO PP20-95, treatment effectiveness was calculated using percent failure (7). Percent failure is calculated by dividing failed length of sealed cracks by total length of sealed cracks. In this study failure point is set as 60 percent treatment effectiveness. Therefore whenever the sealant falls under 60 percent treatment effectiveness the sealant is considered failed.

$$Percent\ Failure = 100 * \frac{Failed\_length}{Total\_length}$$

$$Percent\ Treatment\ Effectiveness = 100 - Percent\ Failure$$

After calculations are performed, a treatment effectiveness versus time graph is plotted. This graph will be helpful in predicting the life of treatment if the effectiveness trend can be extrapolated.

In Atlanta, no newly developed cracks were observed on sections where H1 and H2 sealants were applied. Also, sections with cold pour sealants C1, C2, and C3 did not have any newly developed cracks.

In El Paso, where heavy border traffic is routine, failures were observed on wheel paths. All the failures were observed on sections treated with cold pour sealant.

In Amarillo, failure had a scattered pattern. Failed sections were not confined to certain parts of the pavement. This possibly is due to weather conditions in Amarillo, where freeze/thaw cycles are likely to occur. The C1 sealant section showed excessive failure, while the other sections, H1, H3, and H4, exhibited very good performance.

Failures were observed in cold pour sealed sections in San Antonio. Sections sealed with C1 exhibited newly developed tight cracks. Depression of cold pour sealants was more severe in the test section in this district than in the others.

All sealants showed very good performance in Lufkin. No failure signs were observed in these test sections. As was the case in other districts, cold pour sealants were softer than hot pour sealants.

4.2.2. Covered Sections

Bleeding is the main problem when a pavement is overlaid or chip-sealed after crack treatment. If excessive crack sealant has been placed, the sealing material fills the voids and tends to penetrate through the chip seal surface, creating a shiny glass-like reflecting surface. Strategic Highway Research Program (SHRP) identifies three levels for bleeding:

Low: Coloring of pavement surface is visible.
Moderate: Distinctive appearance with excess asphalt already free.
High: Free asphalt gives the pavement surface a wet look; tire marks are evident.

The SHRP manual recommends measuring the area of the bleeding surface, but in this project only the length of the bleeding sections was measured.

The eight covered sections were monitored for sealant bleeding through the subsequent seal coat. These sections were visually inspected and the rate of bleeding for each sealant type was recorded. Bleeding amount and rate were used to determine the rate of failure, which determines the treatment effectiveness.

Covered test sections in Atlanta and Amarillo were crack sealed in winter 2001. Both cold and hot pour sealants were used in these test sections. After sealing, treated test sections were covered with chip seal in summer 2001. The chip seal applied was AC-15-

5TR binder, which consisted of a minimum of 5 percent ground tire, and then covered with grade 4 aggregate.

Sections in Atlanta and Amarillo were visited 2 months after the chip seal was constructed. In Atlanta, C2 and H1 sealants were applied. Sections treated with H1 showed a low level of bleeding, while no bleeding was observed on the section sealed with C2. In Amarillo, two sealants—C1 and H3—were applied. None of the sections showed bleeding. The chip seal proposed for Lufkin was constructed in summer 2002.

4.3. Long Term Performance of the Test Sections

The American Association of State Highway and Transportation Officials (AASHTO) procedure (AASHTO PP20-95) was adopted to calculate percentage of treatment effectiveness in order to evaluate the performance of the sealants. In this study 60 percent treatment effectiveness was considered as the failure point. The main types of failure considered were opening of sealed cracks, full-depth adhesion or cohesion loss, and spalls.

AASHTO procedures provide a standard practice for evaluating the performance of crack sealing treatment (7). This practice can be used for several types of crack sealants such as cold applied sealants, hot applied sealants, and chemically cured sealants. It also can be used for the selection of crack sealant filler materials, placement configurations, and finishing operations. The projected life of the treatment can be determined by extrapolation of the function of treatment effectiveness versus time.

As illustrated in Figure 4.1, the main product of this evaluation procedure is a chart depicting treatment effectiveness (in percentage) over time. A minimum of one evaluation measurement each year is needed to provide an estimation of the performance of the crack treatment. For the most effective evaluation, measurements should be conducted during the mid-winter period when the crack is subjected to maximum opening. It is suggested that the first inspection be made during the first winter, while another can be done after winter to assess winter damage. Along with traffic control devices, the basic apparatus needed is a distance measurement device like a measuring wheel.

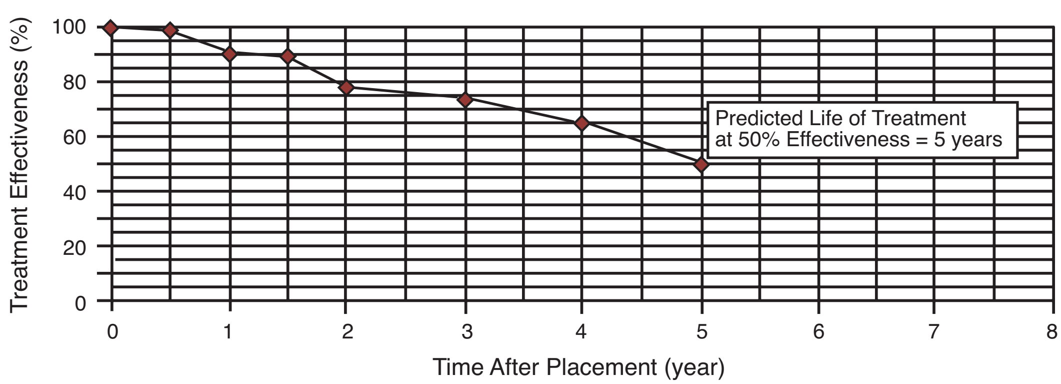


Figure 4.1. Example graph of treatment effectiveness versus time

An unbiased sample of the treated pavement section is used for testing. The sample must not be less than 150 m (492 ft) in length. Generally, pavement sections are grouped according to the type of treatment, sealant, or sealing procedure. When a pavement sample has been previously evaluated, it is best to use the same section for reevaluation in succeeding evaluation procedures. Otherwise, a minimum of five different pavement samples is selected each year.

In this study, the initial lengths of cracks were measured and recorded to the nearest 300 mm (12 inches). A qualitative evaluation was performed by visual examination of cracks, and the type of failure was recorded. Failure can be in the form of full-depth adhesion or cohesion loss, complete pullout, spalls and secondary cracks, potholes, etc. The length of failure of all cracks is measured and recorded during every visit. The treatment effectiveness is the ratio between the length of the remaining sealed crack and the length of the original treatment, expressed as a percentage.

4.3.1. Field Evaluation Results for Non-Covered Test Sections

For the purpose of evaluating the performance of the non-covered sections, five successive investigations were conducted after the first one, for a total of six. Regardless of the district in which the treatment was applied, overall the performance of hot pour sealants was better than that of cold pour sealants.

Atlanta

Five types of sealants were used in this district; two hot pour sealants (H1 and H2) and three cold pour sealants (C1, C2, and C3). C3 is a joint sealant. The treatment was installed on January 31, 2001, on US 290 in Morris County on the southbound, outside lane. The first investigation test for performance evaluation was conducted on May 24, 2001. The other investigations were conducted on February 13 and August 7, 2002, January 23 and August 30, 2003, and February 12, 2004.

The pavement structure of this section was an asphalt concrete overlay on jointed concrete pavement (JCP), where most of the cracks were reflection cracks over the joints. These cracks were spaced transversely and equally at 15 ft (4.5 m). Probably the main cause of the cracks, some of which could be seen, was the heavy truck traffic that caused movements of joints.

Hot pour sealants exhibited excellent performance compared to cold pour sealants in these sections. At the fourth investigation during winter 2003, hot pour sealants H1 and H2 scored a treatment effectiveness of 88.4 percent and 84.8 percent, respectively, and at the fifth investigation during summer 2003, they scored a treatment effectiveness of 90 percent and 86.8 percent, respectively. At the final investigation, during winter 2004, H1 and H2 scored a treatment effectiveness of 73.7 percent and 68.2 percent, respectively.

On the other hand, about one year after construction, cold pour sealants showed an average treatment effectiveness of less than 70 percent when the winter 2002 investigation was conducted. By January 2003, significant failures were observed for cold pour materials. All of the cold pour materials were below 17 percent treatment effectiveness. By the last investigation in February 2004, C3 had a treatment effectiveness of only 6 percent and C1 and C2 exhibited total failure. Figure 4.2 depicts performance trends for the sections in the Atlanta District.

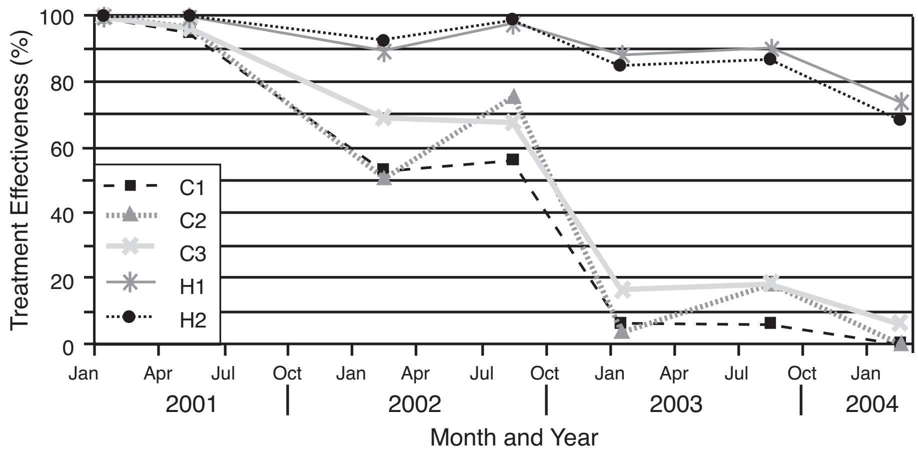


Figure 4.2. Performance trends for sections in Atlanta District

El Paso

Four types of sealants were used in this district, two hot pour sealants (H2 and H3) and two cold pour sealants (C1 and C2). The treatment procedures were performed on May 5, 2001, on Loop 375 in El Paso County on the Border Highway in the eastbound, outside lane. The first investigation was on June 19, 2001. The second and third investigations took place on April 10, 2002, and August 22, 2002, respectively, and the fourth, fifth, and final investigations were carried out on March 27, 2003; August 26, 2003; and February 27, 2004, respectively. These test sections are located in a heavy-truck traffic area by the US-Mexico border. It is observed that most of the failures occurred on the wheel path.

The performance of hot pour sealants surpasses that of cold pour sealants in this district as well. However, in contrast to Atlanta, the treatment effectiveness of the hot pour sealants used in this district (H2 and H3) dropped to 65.1 percent and 76.2 percent, respectively, during the winter 2003 investigation, to 31.7 percent and 61.6 percent during the summer 2003 investigation, and finally to 23.9 percent and 28.4 percent during the winter 2004 investigation. Overall, hot pour sealants in this district dropped from an average treatment effectiveness of 70.6 percent during winter 2003 to an average of 26.15 percent in winter 2004.

The performance of cold pour sealants was in general much lower than that of hot pour sealants. Sealant C2 dropped to a treatment effectiveness of 2.4 percent in the winter 2003 investigation, and experienced total failure by the summer 2003 investigation. Sealant C1 dropped from a treatment effectiveness of 9.7 percent at the winter 2003 investigation to a treatment effectiveness of 2 percent at the summer 2003 investigation, and finally experiencing total failure by the winter 2004 investigation. The performance trends of the sealing materials used in El Paso are shown in Figure 4.3.

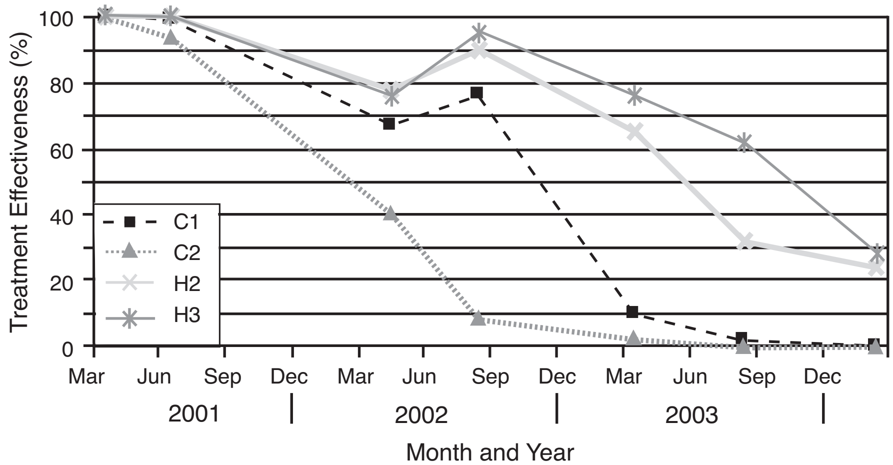


Figure 4.3. Performance trends for the sections in El Paso District

Amarillo

In the Amarillo District, three hot pour (H1, H3, and H4) and two cold pour (C1 and C3) sealants were used. The treatment procedures were undertaken on February 19, 2001, on FM 1151 in Randall County in the eastbound, outside lane. The six investigative visits were made on June 21, 2001; March 31, 2002; August 15, 2002; March 28, 2003; August 25, 2003; and February 26, 2004.

With the exception of H3, hot pour sealants showed excellent performance 15 months after installation in spring 2002. During the fourth and fifth investigations, sealant H1 exhibited a treatment effectiveness of 75.6 percent and 95.5 percent, which then declined to 6 percent at the final visit. Sealant H4 performed best with a final treatment effectiveness of 47 percent during winter 2004 visit. H3, after going from 17.9 percent treatment effectiveness in the fourth investigation to 75.6 percent treatment effectiveness in the fifth investigation, declined to 13.5 percent treatment effectiveness at the final investigation in winter 2004.

At the winter 2002 investigation in this district, the performance of cold pour sealants showed very low values at 0 percent for C1 and 18.6 percent for C2, but at the summer 2002 investigation, the performance of both C1 and C3 showed drastic improvement at 84.3 percent and 90.8 percent treatment effectiveness. This is not an indication of high performance of the material, rather it is simply a mater of cracks closing caused by temperature changes. Nevertheless, by the fourth investigation in winter 2003, C1 and C3 experienced total failure. Figure 4.4 depicts performance trends of the sealants used in test sections in the Amarillo District.

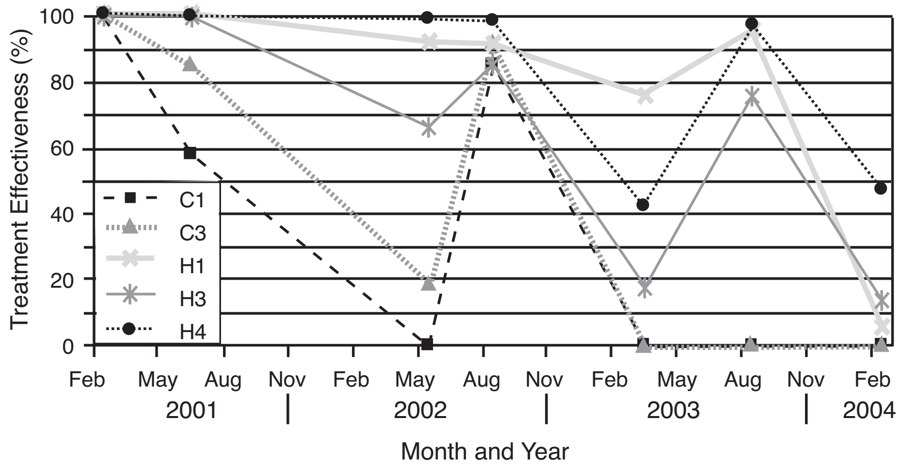


Figure 4.4. Performance trends for the sections in Amarillo District

San Antonio

All seven types of sealing materials were used in treatment procedures in the San Antonio District. Treatment construction started on April 25, 2001, on US 87 in Bexar in the northbound, outside lane. An investigation visit was conducted on July 18, 2001. The next five investigation visits took place on March 8, 2002; September 14, 2002; January 30, 2003; September 11, 2003; and February 20, 2004.

With the exception of the decreasing performance of H2 first apparent during the winter 2002 investigation, and subsequent failure by the final investigation in the winter 2004, hot pour sealants attained a high treatment effectiveness level. H1, H3, and H4 had over 66 percent treatment effectiveness at the final investigation in winter 2004. H3 maintained the highest treatment effectiveness level of 71.2 percent.

Sealant C1 dropped to 0% effectiveness by the winter 2002 visit. Unlike the other two cold pour sealants, the performance of C1 did not improve after the winter 2002 evaluation. Sealants C2 and C3 dropped significantly in treatment effectiveness by the winter 2003 investigation to 8.7 percent and 11.2 percent, respectively, only to rebound slightly to 14.5 percent and 20.8 percent in the summer 2003 investigation. Both had failed completely by winter 2004. Figure 4.5 depicts the performance trends of the sealants used in test sections in the San Antonio District.

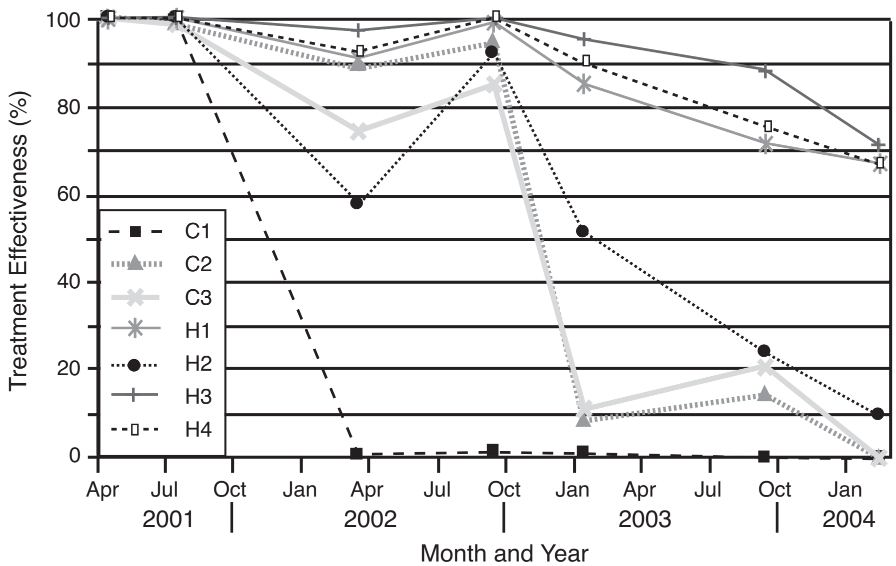


Figure 4.5. Performance trends for the sections in San Antonio District

Lufkin

In the Lufkin District, two cold pour sealants (C2 and C3) and two hot pour sealants (H1 and H4) were installed on February 6, 2001, on US 59 in Polk County in the southbound, outside lane. Afterwards, evaluation tests were conducted six times: May 7, 2001; February 22, 2002; August 20, 2002; January 1, 2003; September 4, 2003; and February 13, 2004.

As was the case in all of the other districts, hot pour sealants maintained treatment effectiveness greater than that of cold pour sealants, scoring an average of 95.1 percent after the second investigation. The high performance of H4 stayed relatively the same. H1 exhibited an increase in treatment effectiveness from 91 percent to 97.1 percent from the winter 2002 evaluation to the summer 2002 investigation, and then experienced a decrease to 86 percent in the winter 2003 investigation. The performance of H4 remained high at 91.1 percent in the winter 2003 investigation.

The performances of both C2 and C3 declined after the first evaluation. At the summer 2002 evaluation, cold pour sealant C2 scored a treatment effectiveness of 98.4 percent, but declined to 23.2 percent at the winter 2003 investigation. The performance of C3 could not be measured at the summer 2002 investigation or after; because this test section had deteriorated significantly, it had been milled and given a new overlay. Figure 4.6 illustrates the performance trends of the sealants used in the sections in Lufkin District.

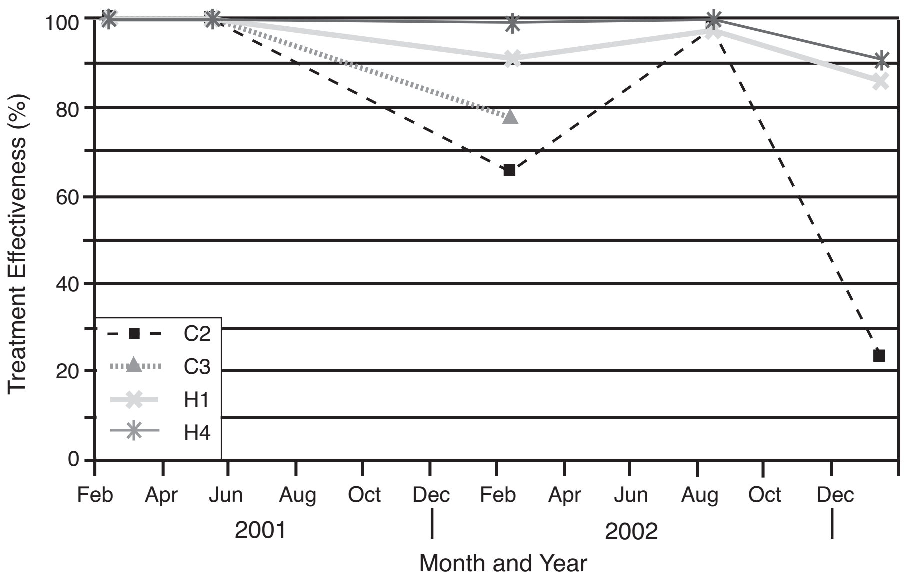


Figure 4.6. Performance trends for the sections in Lufkin District

General Observations

As can be seen from the graphs, an increase in the performance of the sealants was observed during the third and fifth investigations as opposed to an expected decrease in performance with time. This can be attributed to the fact that cracks close during summer months. Also, at high temperatures, the viscosity of the sealing material decreases, which may cause refilling of the generated cracks.

In the case of hot pour sealants, the sealant originally plugs mainly the top part of the crack and does not penetrate all the way down to the crack root. Hence, it is more likely that the failed sections treated with hot pour sealants will recover in high temperatures because of the decrease in viscosity. Because excessive amounts of hot pour sealant usually accumulate near the surface, enough material will be available to seal the failed sections when the viscosity drops.

On the other hand, cold pour sealants have lower viscosity than hot pour sealants at a given temperature. Therefore, when they are applied for the first time, they tend to penetrate the cracks more thoroughly. This leaves less surplus material and subsequently less recovery in the failed sections when the viscosity drops because of high temperatures.

4.3.2. Field Evaluation Results for Covered Test Sections

As mentioned before, these test sections were installed to evaluate the tendency of the sealing materials to bleed through a chip seal or overlay. The test sections were constructed in the Atlanta, Amarillo, and Lufkin districts. Results for the length of bleeding sections on covered test sections based on each visit and district are located in Table 4.1. The method used to evaluate the sections was explained previously in Section 4.2.2.

Atlanta

In Atlanta, crack sealant was applied on January 31, 2001, and chip seal was applied on June 20, 2001, to Loop 281 in Harrison County in the southbound, outside lane. An evaluation was made after 2 months and again on August 8, 2002. These results are analyzed in Research Report 4061-2. This section was evaluated two more times on August 30, 2003, and February 12, 2004.

Before applying chip seal, the test sections were treated using hot pour sealant H1 and cold pour sealant C2. Sections treated with H1 showed bleeding at a low-severity level. The length of the bleeding portions was 590 ft in summer 2003 and 650 ft in winter 2004. Sections treated with C2 exhibited no bleeding problems throughout the project.

Amarillo

This test section, located in Randall County on FM 1541 in the southbound, outside lane, was crack sealed on February 20, 2001, with cold pour sealant C1 and hot pour sealant H3. The chip seal was applied on August 17, 2001, and the test section was visited for evaluation 2 months after the chip seal. The test sections were then investigated again on August 15, 2002; August 28, 2003; and February 26, 2004. Once more, the hot pour sealant seemed to engender a bleeding problem. During the summer 2002 investigation, the severity of the bleeding was very low. The bleeding observed then increased to 1,450 ft during the summer 2003 visit and to 1,560 ft during the winter 2004 visit. On the other hand, the test section that was treated with C1 did not show any bleeding problems in any of the visits.

Lufkin

This test section, located in Polk County on US 190 in the westbound, outside lane was crack sealed on February 7 and 8, 2001, and then was chip sealed on June 25, 2002. It was investigated on August 20, 2002; September 4, 2003; and February 13, 2004. Two cold pour sealants (C1 and C2) and two hot pour sealants (H1 and H3) were used for crack treatment of this test section. As expected, bleeding was observed on the hot pour treated sections. However, its severity was very low. Bleeding portion lengths were 289 ft and 310 ft for H1 in summer 2003 and winter 2004, respectively. They were 216 ft and 233 ft for H3 in summer 2003 and winter 2003, respectively. In the case of cold pour sealants, no signs of bleeding were observed.

Summary

All of the bleeding observed in this project was on hot pour sections. The bleeding amount increased with time except for H1 in the Atlanta District between the first and second visit. The first observation in Atlanta was on a rainy day and therefore bleeding was more obvious. That is why in the first field trip we observed a high rate of bleeding in this test section. In all hot pour sections, bleeding was observed regardless of the district or the material type. Even if we observed bleeding only in hot pour sections, this bleeding was at a very low level. No bleeding was observed on cold pour sections throughout the project. Length of bleeding for sections per district is detailed in Table 4.1.

Table 4.1. Length of Bleeding Sections on Covered Sections by District and Visit

District	Sealant	First Visit Summer 2001	Second Visit Summer 2002	Third Visit Summer 2003	Fourth Visit Winter 2004
Atlanta	C2	0	0	0	0
	H1	700	407	590	650
Amarillo	C1	0	0	0	0
	H3	0	0	1450	1560
Lufkin	C1	0	0	0	0
	C2	0	0	0	0
	H1	0	214	289	310
	H3	0	150	216	233

4.4. Discussion of Results

The findings of this study were obtained from field visits to the test sections in the five districts throughout a period of 4 years. The first evaluations were conducted within 3 to 4 months after crack sealants were placed. Subsequent evaluations took place over the course of 3 years. This discussion of the results aims to understand and explain the performance trends of the sealing materials. The overall average values of the findings for the treatment effectiveness for each sealant for non-covered sections at each stage are shown in Appendix D.

In the summer 2001 investigation, it was found that the overall performance of hot pour sealants was slightly better than that of cold pour sealants. The average values for the treatment effectiveness of each sealant can be found in Figure D.1. Across the districts, all hot pour sealants had the best results, scoring an average treatment effectiveness level of approximately 100 percent. With the exception of Amarillo, where C1 performed with 87.7 percent treatment effectiveness, cold pour sealants exhibited an overall average treatment effectiveness of greater than 90 percent.

After the first visits, the performance evaluation involved investigative visits each summer and winter for the next 3 years. The remaining investigation results of the test sections in terms of average treatment effectiveness for each sealant per visit are also included in Appendix D in Figures D.2 through D.6.

During the second investigation in winter 2002, it was found that the performance of hot pour sealants continued to be better than that of cold pour sealants in every district. The average values for treatment effectiveness of each sealant can be found in Figure D.2. Hot pour sealant H4 performed the best with a treatment effectiveness average of 96.4 percent. Cold pour sealant C1 had the least resistance to traffic and environmental influences, with a treatment effectiveness level of 30.3 percent 1 year after installation. The results show a general decrease in treatment effectiveness for all the sealants. However, the decrease is much more rapid for cold pour sealants.

Similar trends were observed in the remaining visits to the test sections throughout the project. The third investigation was conducted about 18 months after construction, during the summer 2002. The fourth, fifth, and sixth investigations were conducted during winter 2003, summer 2003, and winter 2004. By the fourth investigation, all cold pour sealants went below a treatment effectiveness level of 60 percent, and hot pour sealants were performing better comparatively. The average results of the third, fourth, fifth, and sixth investigations are shown in Figures D.3, D.4, D.5, and D.6, respectively.

The results from the final investigation in winter 2004 are shown in Table 4.2. In the Atlanta District in the final investigation, H1 and H2 scored a treatment effectiveness of 73.7 percent and 68.2 percent, respectively. In the El Paso District, H2 and H3 had a treatment effectiveness of 23.9 percent and 28.4 percent, respectively, during the final investigation. They had an average treatment effectiveness of 26.15 percent. In contrast, cold pour sealants performed much lower comparatively. Sealant C2 had experienced total failure before the final investigation in winter 2004, and C1 exhibited total failure in the winter 2004 visit.

In the Amarillo District, sealant H4 showed the best performance in the final visit, with a final treatment effectiveness of 47 percent. The other hot pour sealants, H1 and H3, had a treatment effectiveness of 6 percent and 13.5 percent, respectively, during the final visit in winter 2004. Cold pour sealants C1 and C3 experienced total failure before the final investigation in winter 2003. Finally, in the San Antonio District, hot pour sealants attained a high treatment effectiveness level in the final investigation. Hot pour sealants had an average treatment effectiveness level of 68 percent, with H1 maintaining the highest treatment effectiveness level of 71.2 percent. The cold pour sealants, on the other hand, had all failed by the final investigation. Test sections in Lufkin were not evaluated after the summer 2002 investigation because the sections had been given a new overlay.

Hot pour sealants performed better than cold pour sealants in every district. All cold pour sealants in all districts showed very low performance, with only one in the Atlanta District showing 6 percent treatment effectiveness in the final visit with the rest at 0 percent. The overall average treatment effectiveness for cold pour materials was 0.52 percent at the end of the winter 2004 visit. Hot pour materials, on the other hand, had an average treatment effectiveness of 42.95 percent at the end of the winter 2004 visit.

In a comparison of individual sealants, H4 (a joint sealant) achieved the best overall treatment effectiveness of 56.75 percent, whereas C2 achieved the lowest overall treatment effectiveness at 0 percent. Hot pour materials did not go below the 34 percent treatment effectiveness level, with a range from 33.87 percent to 56.75 percent.

Sealants also performed differently in different districts with varying environmental and traffic conditions. As previously mentioned, the El Paso test section is located along the Mexico border where there is heavy truck traffic. The hot pour sealants placed on the test sections in the El Paso District had higher failure rates than hot pour sealants placed in other districts, perhaps because of the effect of heavy truck traffic at the border. In addition, in the Amarillo District, there was a greater fluctuation in treatment effectiveness levels between winter and summer investigative visits than experienced in other districts. In Amarillo, most cracks sealed were low temperature (thermal) cracks, which move according to pavement temperature differences.

Table 4.2. Treatment Effectiveness Evaluation Results for the Performance after the Final Investigation (Winter 2004)

	Treatment Effectiveness (%)					
	Final (6th) Visit (Winter 2004)					
Sealant Material	***Atlanta***	***El Paso***	***Amarillo***	***San Antonio***	***Lufkin***	**AVG.**
C1	0.2	0	0	0.1	N/A	0.07
C2	0	0	N/A	0	N/A	0.00
C3	6	N/A	0	0	N/A	2.00
H1	73.7	N/A	6	67	N/A	48.91
H2	68.2	23.9	N/A	9.5	N/A	33.87
H3	N/A	28.4	13.5	71.2	N/A	37.70
H4	N/A	N/A	47	66.5	N/A	56.75
Date of investigation	2/12/2004	2/27/2004	2/26/2004	2/20/2004	2/13/2004	
AVG. for Cold Pour	2.06	0.00	0.00	0.03	N/A	0.52
AVG. for Hot Pour	70.95	26.15	21.17	53.55	N/A	42.95
Overall AVG.	29.62	13.07	13.30	30.61	N/A	21.65

Chapter 5. Cost Analysis

5.1. Crack Seal Installation Cost Analysis

The cost analysis for this project is based on the comparison of all aspects related to the placement of hot and cold pour sealants on five highways in Texas. The test sections included in the cost comparison were ones that were not covered with a seal coat throughout the duration of the project. The average annual cost (AAC) values were calculated for each sealant in twenty-five test sections in five districts.

In this study, the initial cost analysis also was done only for the non-covered test sections. Initial cost values were calculated based on sealing materials, equipment for traffic control, sealing equipment, hot pour equipment, and crew labor costs. Initial construction cost values used in this report were taken from Report 4061-1. More detailed information about the initial cost analysis and its calculations can be found in Research Report 4061-1 (8).

5.2. Life-Cycle Cost Analysis

Construction cost is not the sole factor in cost-effectiveness. Performance of a sealant is also another significant factor, because a poorly performing sealant will require sealing to occur more often. Based on the service-life information collected from field evaluations, life-cycle costs can be calculated. However, a life-cycle cost analysis can only be done when all the treatments reach the failure point. For this analysis, the failure point was considered to be when the treatment effectiveness of the sealant went below 60 percent. Based on this criterion, the service life for each sealant in each district was calculated and included in Appendix E. At the end of the last field visit some of the hot pour materials had not failed. For those materials, based on the treatment effectiveness information collected previously, service life was estimated by an extrapolation of the treatment effectiveness versus time curve.

In this analysis, the results obtained between different districts were similar except for the Amarillo District. The cost per foot of the given sealant was inversely proportional to the crack length of the section being sealed. Thus, a longer crack length resulted in a lower cost per foot and alternately, a shorter crack length resulted in a higher cost per foot. This case was more evident in the Amarillo District where the total crack length being sealed was 2,800 ft., while the other test sections' lengths were around 10,000 ft. Because the test sections built in Amarillo had a much higher initial cost value than the rest of the test sections, in this chapter the values from the other four sections are discussed. The AAC values for Amarillo were calculated and reported separately in Table E.3 in Appendix E.

In this section, cost-effectiveness was calculated based on the explanations provided in SHRP-H-348 "Materials and Procedures for Sealing and Filling Cracks in Asphalt-Surfaced Pavements" (9). AAC values were calculated based on a 3.0 percent interest rate. Tables E.1 through E.5, showing the results of these calculations, were included in Appendix E. Average values for AAC and their standard deviations and construction cost (CC) and AAC for 50,000 ft imaginary length values from the 4061-1 report are included in Table 5.1 (8).

Table 5.1. Cost-Effectiveness

Sealant	CC for 50,000 ft Imaginary Length ($)	AAC for 50,000 ft Imaginary Length ($)	Average AAC ($/ft)	Std. Deviation
C1	5256	6526	0.131	0.068
C2	6060	5779	0.116	0.077
C3	5789	3780	0.076	0.002
H1	4288	1360	0.027	0.008
H2	5573	4037	0.081	0.071
H3	4611	1825	0.037	0.025
H4	5393	1831	0.037	0.000

Figure 5.1 compares the average AAC values for 50,000 ft imaginary length for different materials in the four different districts. The AAC values for 50,000 ft imaginary length from the Amarillo District were not included for the calculation in Table 5.1. As can be seen in this figure, overall AAC values for 50,000 ft imaginary length for cold pour materials are higher than those for hot pour materials. The only exception to this is the AAC value for 50,000 ft imaginary length of the H2 material in the San Antonio District. The H2 material in this district showed a very low performance and failed in less than a year after construction. Other than this specific situation, in all cases, hot pour materials showed lower AAC values for 50,000 ft imaginary length than cold pour materials.

Among the hot pour materials, the lowest AAC values for 50,000 ft imaginary length were observed for material H1. Hot pour materials used in the El Paso test section, H2 and H3, showed relatively higher AAC values for 50,000 ft imaginary length compared to other sections. Among the cold pour materials, the lowest AAC values for 50,000 ft imaginary length were observed for C3. The overall average AAC for 50,000 ft imaginary length for cold pour materials is $5,362 with a standard deviation of 2981, and for hot pour materials, the average AAC for 50,000 ft imaginary length is $2,263 with a standard deviation of 2089. The individual AAC for 50,000 ft imaginary length comparison for each district including Amarillo is presented in Appendix E, Tables E.1 through E.5.

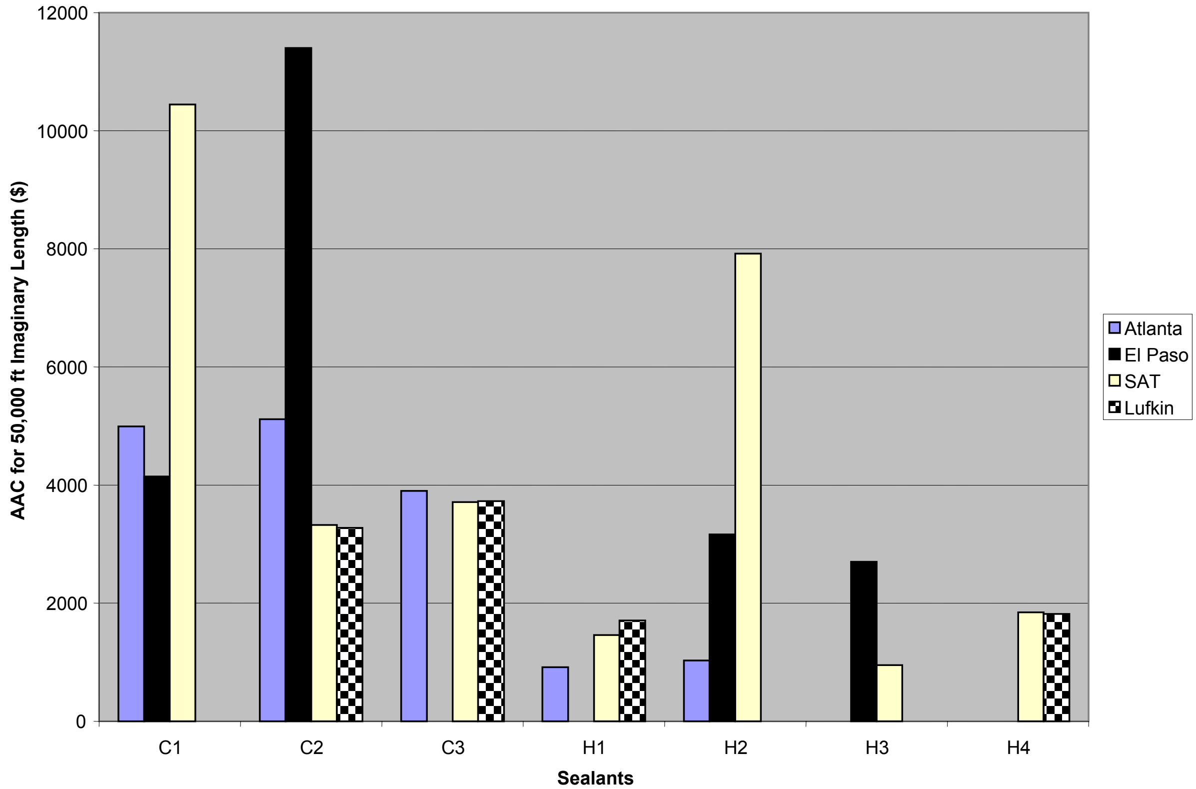


Figure 5.1. Average annual cost values for 50,000 ft imaginary length for each sealant

Chapter 6. Recommended Changes to Material Specifications

Currently, the Texas Department of Transportation (TxDOT) uses four different specifications regarding crack and joint sealants. Special specification Item 3127 deals with cold pour crack sealants. Under this specification, sealants comply with requirements on viscosity, storage stability, sieve test, and percent residue from evaporation. According to this specification, the residue should also meet requirements on penetration, softening point, and ductility.

Hot pour rubber asphalt crack sealant is covered under specification Item 300 under Classes A and B, and under Types I, II, and III. Class A materials satisfy requirements on penetration and softening point, and Class B also meets requirements on the bond test.

TxDOT DMS-6310 specification deals with joint sealants in 10 different classes. In this study, materials satisfying class 3 and class 9 DMS-6310 specifications were utilized. Sealers meeting class 9 criteria satisfy requirements on viscosity and percent residue from evaporation. The residue complies with requirements on penetration, softening point, and bond. The bond test is conducted at 0 ºF and is considered to pass specification requirements if it can take three cycles of bond test. After the bond and extension test, there shall be no evidence of cracking, separation, or other opening that is over 3 millimeters deep at any point in the sealer or between the sealer and test blocks. Materials satisfying DMS-6310 class 3 specifications should comply with requirements on penetration, flow, resilience, and bond tests. In this study, sealants satisfying class 3 and class 9 DMS-6310 specifications were applied to cracks in the asphalt pavement.

Seven different materials were investigated in this study. Sealants C1 and C2 satisfy the requirements for specification item 3127. Hot pour sealants H1 and H3 satisfy Item 300, Class A requirements and H2 meets Item 300, Class B requirements. The cold pour polymer-modified asphalt emulsion joint seal (sealant C3 in Tables 3.1 and 3.2) meets requirements for DMS-6310, Class 9. Sealant H4 is a hot pour joint sealant meeting DMS-6310, Class 3 requirements. Both sealants C3 and H4 are intended for portland cement concrete pavement joints and the joints between concrete and asphalt pavements. However, in this study they were applied to cracks in asphalt pavement.

6.1. Field Performance

In this study, mainly cohesive and adhesive failures were observed at the field visits. *Cohesive failure* describes cracking through the applied material. Both cold pour and hot pour sealants experienced this failure. *Adhesive failure* can be described as failure that causes the sealant to separate from the pavement. This type of failure was observed mostly with cold pour sealants that are applied into the crack.

Another type of failure observed in this study was sealant erosion. *Sealant erosion* occurs where traffic wears away at the surface of the sealant. In general, it occurs in hot pour application when excessive sealant material on top of the crack is exposed to heavy traffic. It is observed that overall hot pour materials showed lower performance in El Paso where there was heavy border truck traffic.

The depth of cold pour application prevents this erosion from significantly impacting performance for this kind of sealant. After application to the cracks, cold pour and hot pour materials show different configurations in the crack. Cold pour materials penetrate into the crack, while in most cases hot pour materials stay on top of the pavement and form a cap over the crack. This difference between the cold and hot pour materials is illustrated in Figure 6.1.

Possible lab tests to estimate the propensity of each material to these failures would contribute greatly to the field performance of cold pour and hot pour sealants.

Figure 6.1. Configuration of cold pour and hot pour materials in the crack

6.2. Tests in the Specifications

Current testing methods to characterize cold pour and hot pour materials focus on cohesion, adhesion, cold temperature properties, elasticity, and viscosity. All sealants utilized in this study were tested by the Brookfield test, percent residue evaporation, rubber content, flash point, penetration at 39.2 °F and 77 °F, resilience, flow, ductility softening point, and bond tests. Material specifications utilize these test methods to rate cold pour and hot pour performance quality. However, an unfortunate fact with each of these test methods is that sample results do not predict sealant performance in the field. To characterize the sealants in addition to what is available in the specifications, the following equipment can be evaluated.

- The *bending beam rheometer* (BBR*)* test examines sealant performance in cold temperatures. This study showed that the main failures for sealants occur with cold temperatures during the winter. Therefore, it is very important to understand their behavior at cold temperatures. This test can be utilized for both hot and cold pour sealants.
- *Bond tests* analyze cohesion and adhesion of sealants to the pavement. Bond tests might be good methods to evaluate the potential for adhesive failure for sealants.
- The *dynamic shear rheometer* (DSR) test investigates a sealant's elastic and viscous behavior. The DSR equipment can be utilized to characterize hot pour sealants.

Chapter 7. Conclusions

This report concludes a 4-year research project comparing cold pour and hot pour rubber crack sealants. A survey on crack sealants was conducted for twenty-one districts in Texas and nine state departments of transportation. In the first year, thirty-three test sections in five districts were constructed and the long-term performance of seven different sealants was monitored for 3 years. The performance was evaluated starting from the first 4 months after the construction of the treatment. Installation and lifetime costs were analyzed for the different types of sealants, and recommendations were made to modify Texas Department of Transportation (TxDOT) specifications.

The survey of districts showed that all participating districts used hot pour sealants, whereas only one-third of the districts used cold pour sealants. Overall, it is reported that the hot pour sealants performed better than the cold pour sealants. For most of the performance evaluation questions, neither hot pour nor cold pour were ranked poor by the participating districts. Hot pour sealants were ranked poor or fair for resistance to bleeding by the majority of the districts.

The survey of states showed that all participating states used hot pour sealants. Only five of nine participating states reported using cold pour sealants. For two-thirds of the questions, cold pour sealants were ranked poor by some of the participating states. Hot pour sealants were ranked poor only for resistance to bleeding by some of the states. In an overall evaluation of the survey, it is reported that hot pour sealants performed better than cold pour sealants. The questionnaire used for the survey is included in Report 4061-1 (8).

Test sections were crack sealed in five Texas districts between January and April 2001. The sections were first visited approximately 3 to 4 months after construction. Overall, the first evaluations of both hot pour and cold pour materials indicated that they perform well. In the first visits to covered sections, no bleeding was observed. The initial results of the not-covered sections indicated very good performance of hot pour sealants. While cold pour sealants in most cases exhibited good behavior, in other cases failures were observed.

In the summer 2001 investigation, it was found that the overall performance of hot pour sealants was slightly better than that of cold pour sealants. Across the districts, all hot pour sealants had the best results, scoring an average treatment effectiveness level of approximately 100 percent. With the exception of Amarillo, where C1 performed with 87.7 percent treatment effectiveness, the cold pour sealants exhibited an overall average treatment effectiveness of greater than 90 percent.

During the second investigation in winter 2002, it was found that the performance of hot pour sealants continued to be better than that of cold pour sealants in every district. The results show a general decrease in treatment effectiveness for all the sealants. However, the decrease is much more rapid for cold pour sealants. Similar trends were observed in the remaining visits to the test sections throughout the project. By the fourth investigation, all cold pour sealants went below a treatment effectiveness level of 60 percent, and hot pour sealants were performing better comparatively.

The long-term evaluation of the test sections indicated that hot pour sealants perform better over time than cold pour sealants. The results from the final investigation in winter 2004 show that hot pour sealants performed better than cold pour sealants in every district. All cold pour sealants in all districts showed very low performance, with only one in the Atlanta District showing 6 percent treatment effectiveness in the final visit with the rest at 0 percent. The overall average treatment effectiveness for cold pour materials was 0.52 percent. Hot pour materials, on the other hand, had an average treatment effectiveness of 42.95 percent.

The cost analyses showed that the overall average annual cost (AAC) for 50,000 ft imaginary length for cold pour materials is $5362 with a standard deviation of 2981, and for hot pour materials, the average AAC for 50,000 ft imaginary length is $2263 with a standard deviation of 2089. Among the hot pour materials, the lowest AAC values for 50,000 ft imaginary length were observed for material H1. Hot pour materials used in the El Paso test sections, H2 and H3, showed relatively higher AAC for 50,000 ft imaginary length values compared to other sections. Among the cold pour materials, the lowest AAC values for 50,000 ft imaginary length were observed for C3 (a joint sealant). The initial construction cost analysis for 50,000 ft imaginary length presented in the research report 4061-1. The cost analysis showed that the overall initial construction cost (CC) for cold pour materials is $5702 with a standard deviation of $409, and for hot pour materials, the average initial construction cost is $4966 with a standard deviation of $615 for 50,000ft imaginary length. The initial sealing cost typically should not be the deciding economic factor for the selection of the sealant type. In this study the initial cost values were considered with respect to sealant performance and were used in the life-cycle cost analysis. While performance is important, cost-effectiveness is often the deciding factor in determining which materials and procedures to use.

Modifications to the specifications for crack sealants currently used at TxDOT were suggested. These modifications include characterizing the sealants by using the bending beam rheometer (BBR) test and the dynamic shear rheometer (DSR) test, in addition to what is available in the specifications. This study showed that the main failures for sealants occur at cold temperatures during the winter. Therefore, it is very important to understand the sealants behavior at cold temperatures. Because the BBR examines sealant performance in cold temperatures, this test can be utilized for both hot and cold pour sealants.

In this study, adhesive failures were observed mainly for cold pour materials. Bond tests analyze cohesion and adhesion of sealants to pavement. Bond tests might be good tests to evaluate the potential for adhesive failure in cold pour sealants. DSR investigates sealants' elastic and viscous behavior. The DSR equipment can be utilized to better characterize hot pour sealants.

References

1. Smith, K. L., and A. R. Romine, *"LTPP PAVEMENT MAINTENANCE MATERIALS: SHRP CRACK TREATMENT EXPERIMENT,"* FINAL REPORT, ERES Consultants, Incorporated, Federal Highway Administration, Turner Fairbank Hwy Research Center, Report Number: FHWA-RD-99-143, 1999.

2. Masson, J. F, and M. A. Lacasse, *"EFFECT OF HOT-AIR LANCE ON CRACK SEALANT ADHESION,"* Journal of Transportation Engineering, American Society of Civil Engineers, 1999.

3. Bruggeman, G. E., S. Voigt, and C. Magnusson, *"ASPHALT PAVEMENT CRACK FILLING IN NORTHERN MINNESOTA,"* Sixth International Conference on Low-Volume Roads, Minneapolis, Minnesota, Federal Highway Administration, 1995.

4. Ward, D. R., *"EVALUATION OF CRACK SEALANT PERFORMANCE ON INDIANA'S ASPHALT CONCRETE SURFACED PAVEMENTS,"* FINAL REPORT, Indiana Department of Transportation, Division of Research; Federal Highway Administration, 1993.

5. Chichak, M., *"HOT-APPLIED RUBBER-MODIFIED CRACK SEALER USE IN ALBERTA,"* Alberta Transportation and Utilities, Research and Development Branch, 1993.

6. Eaton, R. A., and J. Ashcraft, *"STATE-OF-THE-ART SURVEY OF FLEXIBLE PAVEMENT CRACK SEALING PROCEDURES IN THE UNITED STATES,"* Report Number: CRREL Report 92-18, Cold Regions Research and Engineering Laboratory, 1992.

7. *"STANDARD PRACTICE FOR EVALUATING THE PERFORMANCE OF CRACK SEALING TREATMENT ON ASPHALT SURFACED PAVEMENTS,"* AASHTO Designation: PP20-95, 2000.

8. Yildirim, Y., M. Solamanian, and T. Kennedy, 2002. *"COMPARISON OF HOT RUBBER CRACK SEALANTS TO EMULSIFIED ASPHALT CRACK SEALANTS."* Research Report 4061-1. Center for Transportation Research, The University of Texas at Austin, Austin, TX.

9. Smith, Kelly and A. Russell Romine, *"MATERIALS AND PROCEDURES FOR SEALING AND FILLING CRACKS IN ASPHALT-SURFACED PAVEMENTS,"* SHRP-H-348, April 1994.

Appendix A: Materials

Table A.1. Laboratory Test Results for Sealants Used in Test Sections

Properties	C1 (Crack Sealant)	C2 (Crack Sealant)	C3 (Joint Sealant)	H1 (Crack Sealant)	H2 (Crack Sealant)	H3 (Crack Sealant)	H4 (Joint Sealant)
BrkF Viscosity at 77 ˚F (Centipoise)	12900	13600	32560	N/A	N/A	N/A	N/A
Granulated Vulcanized Rubber Content (%)	0	0	0	25.8	14.6	24.6	0
Evaporation Residue (%)	67.8	65	67	N/A	N/A	N/A	N/A
Penetration at 39.2˚F	12	12	14	13	21	11	48
Penetration at 77˚F	42	45	60	34	47	33	82
Resilience at 77 ˚F (%)	15	23	20	59	69	54	72
Ductility at 39.2 ˚F (cm)	100+	100+	100+	7.5	16	8	49
Bond Test	Failed	Failed	Passed	Failed	Passed	Failed	Passed
Flow at 77 ˚F (mm)	5+ (Fail)	5+	5+	5+	5+	5+	Passed
Flash Point (˚F)	455	540	580	400	540	410	415
Softening Point (˚F)	202	158	160	168	183	155	190

Appendix B: Specifications

Table B.1. Item 3127, Cold Pour Crack Sealants

Properties	Minimum	Maximum	Test Procedure
Viscosity, Brookfield, 77 °F, Centipoise	10,000	25,000	ASTM D 2196 Method A
Storage Stability Test One Day, Percent	-	1	AASHTO T 59
Sieve Test, Percent	-	0.10	AASHTO T 59
Evaporation Residue, Percent	65	-	
Penetration, 25C (77 °F) 100 G, 5 seconds, (0.1mm)	35	75	AASHTO T 49
Softening Point, R & B.,°F	140	-	AASHTO T 53
Ductility, 39.2 °F 5 cm/min, cm	100	-	AASHTO T 51

Table B.2. Item DMS-6310, Class 9, Joint Sealants and Seals, Polymer-Modified Asphalt Emulsion Joint Seal

Properties	Minimum	Maximum	Test Procedure
Viscosity, Brookfield, 25C (77 °F) Pa*s	30	70	ASTM D 2196 Method A
Evaporation Residue, Percent	65	-	Residue evaporation Procedure
Penetration, 25C (77 °F) 100 G, 5 seconds, (0.1mm)	35	75	AASHTO T 49
Softening Point, F & B., C (°F)	70 (160)	-	AASHTO T 53
Bond, 3 cycles at –17.8C (0 °F), 50% extension	Pass		TEX-525-C.

Table B.3. Item DMS-6310, Class 3, Joint Sealants and Seal, Hot-Poured Rubber

Properties	Minimum	Maximum	Test Procedure
Penetration, 25C (77 °F) 150 G, 5 seconds, (0.1mm)	-	90	TEX-525-C
Flow (5h, 60C [140 °F]), 75 degree incline	-	3 mm (1/8 in.)	TEX-525-C
Resilience: 25C (77 °F), original material, Percent	60		TEX-525-C
Bond, 3 cycles at -29C (-20 °F)	Pass		TEX-525-C.

Table B.4. Item GSD 745-80-25, Rubber Asphalt Crack Sealing Compound

Percent Retained

Sieve Size	**Type I**	**Type II**	**Type III**
2.36mm (No. 8)	0	0	-
2.00 mm (No. 10)	0-5	-	0
600 µm (No. 30)	90-100	50-70	45-60
300 µm (No. 50)	95-100	70-95	75-90
150 µm (No. 100)	-	95-100	90-100

Table B.5. Item GSD 745-80-25, Class A, Rubber Asphalt Crack Sealing Compound

Properties	**Minimum**	**Maximum**	**Test Procedure**
Rubber Content			
Granulated vulcanized rubber, percent by weight	22	26	
Virgin rubber polymer, percent by weight			
Penetration, 25C (77 °F) 100 G, 5 seconds, (0.1mm)	30	50	ASTM D5 except the cone specified in ASTEM D217 shall be substituted for the penetration needle
Penetration, 0C (32 °F), 200g. 60 sec	12	-	ASTM D5 except the cone specified in ASTEM D217 shall be substituted for the penetration needle

Table B.6. Item GSD 745-80-25, Class B, Rubber Asphalt Crack Sealing Compound

Properties	**Minimum**	**Maximum**	**Test Procedure**
Rubber Content			
Granulated vulcanized rubber, percent by weight	13	17	
Virgin rubber polymer, percent by weight	2	-	
Penetration, 25C (77 °F) 100 G, 5 seconds, (0.1mm)	30	50	ASTM D5 except the cone specified in ASTEM D217 shall be substituted for the penetration needle
Penetration, 0C (32 °F), 200g. 60 sec	12	-	ASTM D5 except the cone specified in ASTEM D217 shall be substituted for the penetration needle
Softening Point: R&B	76.6C (-170°F)	-	
Bond: 3 cycles at -6.7C (20 °F)			TEX-525-C

Appendix C: Test Section Locations and Dates Visited

Table C.1. Dates for Construction and Visits for Non-Covered Test Sections

	Atlanta	El Paso	Amarillo	San Antonio	Lufkin
Construction	1/31/2001	3/5/2001	2/19/2001	4/25/2001	2/6/2001
1. Summer 2001	5/24/01	6/19/2001	6/21/2001	7/18/2001	5/7/2001
2. Winter 2002	2/13/2002	4/10/2002	5/31/2002	3/8/2002	2/22/2002
3. Summer 2002	8/8/2002	8/22/2002	8/15/2002	9/14/2002	8/20/2002
4. Winter 2003	1/23/2003	3/27/2003	3/28/2003	1/30/2003	1/24/2003
5. Summer 2003	8/30/2003	8/26/2003	8/25/2003	9/11/2003	9/4/2003
6. Winter 2004	2/12/2004	2/27/2004	2/26/2004	2/20/2004	2/13/2004

Table C.2. Dates for Construction and Visits for Covered Test Sections

	Atlanta	Amarillo	Lufkin
Construction	1/31/2001	2/20/2001	2/7/2001
Chip Seal	6/20/01	8/17/2001	6/25/2002
1. Summer 2002	8/8/2002	8/15/2002	8/20/2002
2. Summer 2003	8/30/2003	8/25/2003	9/4/2003
3. Winter 2004	2/12/2004	2/26/2004	2/13/2004

Figure C.1. Non-Covered test sections in Amarillo District

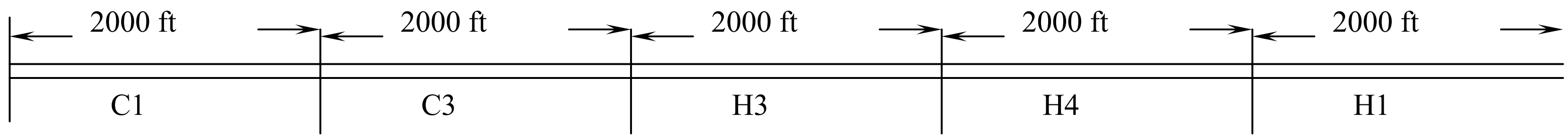
District: Amarillo
County: Randall

Sealing Dates: 2/19/01 and 2/20/01

Highway: FM 1151

Location: East Bound, Outside Lane

<u>Construction Sequence for Sealants</u>



<u>CODES:</u>

C1: Item 3127, Crack Seal ***<u>Cold</u>*** Pour

C3: DMS-6310, Class 9, Joint Seal ***<u>Cold</u>*** Pour

H3: GSD 745-80-25, Crack Seal ***<u>Hot</u>*** Pour, Type I, Class A

H4: DMS-6310, Class 3, Joint Seal ***<u>Hot</u>*** Pour

H1: GSD 745-80-25, Crack Seal ***<u>Hot</u>*** Pour, Type I, Class A

Figure C.2. Covered test sections in Amarillo District

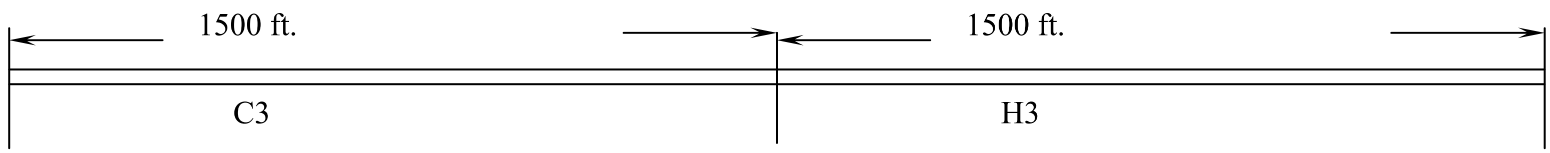
District: Amarillo
County: Randall

Sealing Date: 2/20/01

Highway: FM 1541

Location: South Bound, Outside Lane

Construction Sequence for Sealants



CODES:

C3: DMS-6310, Class 9, Joint Seal ***Cold*** Pour

H3: GSD 745-80-25, Crack Seal ***Hot*** Pour, Type I, Class A

NOTES:

Originally, C2 was scheduled for this road. However, no C2 was delivered to Amarillo. So, C3 was used instead.

During the visit of November 2000, each segment was considered to be 3,000 feet long. However, because of the extension of cracking, each segment length was reduced to 1,500 feet.

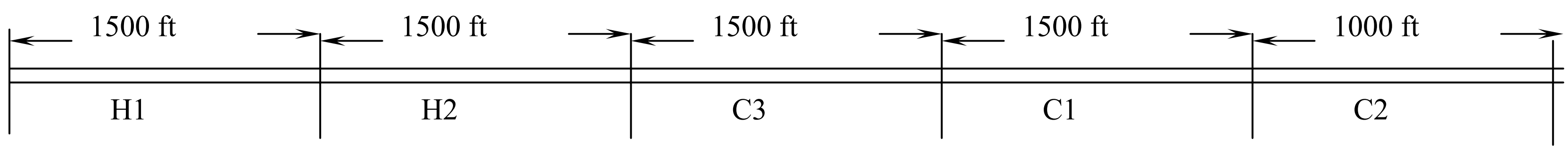
The road had bleeding in many areas on the wheel path at the time of sealing. This should be taken into consideration for analysis.

Figure C.3. Non-Covered test sections in Atlanta District

District: Atlanta
County: Morris
Sealing Dates: 1/30/01 and 1/31/01

Highway: US 259
Location: South Bound, Outside Lane

<u>Construction Sequence for Sealants</u>



<u>CODES:</u>

H1: GSD 745-80-25, Crack Seal ***<u>Hot</u>*** Pour, Type I, Class A

H2: GSD 745-80-25, Crack Seal ***<u>Hot</u>*** Pour, Type III, Class B

C3: DMS-6310, Class 9, Joint Seal ***<u>Cold</u>*** Pour

C1: Item 3127, Crack Seal ***<u>Cold</u>*** Pour

C2: Item 3127, Crack Seal ***<u>Cold</u>*** Pour

Figure C.4. Covered test sections in Atlanta District

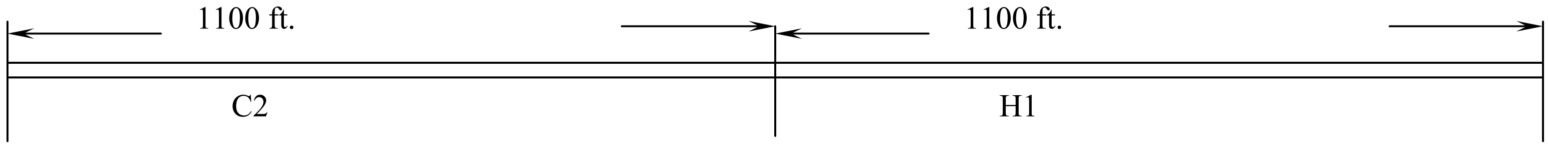
District: Atlanta
County: Harrison

Sealing Date: 1/31/01

Highway: Loop 281

Location: South Bound, Outside Lane

Construction Sequence for Sealants



CODES:

C2: Item 3127, Crack Seal ***Cold*** Pour

H1: GSD 745-80-25, Crack Seal ***Hot*** Pour, Type I, Class A

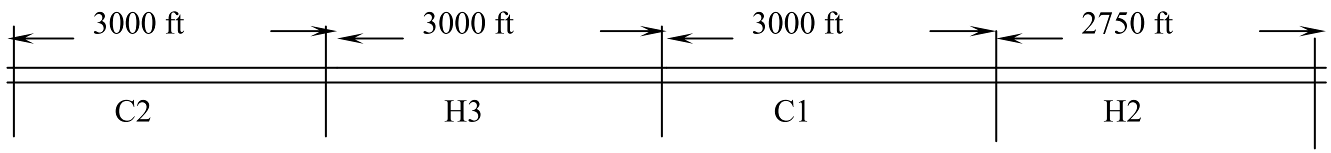
Figure C.5. Non-Covered test sections in El Paso District

District: El Paso
County: El Paso

Sealing Dates: 3/5/01 and 3/6/01

Location: East Bound, Outside Lane
Highway: Loop 375 (Border Highway)

<u>Construction Sequence for Sealants</u>



<u>CODES:</u>

C2: Item 3127, Crack Seal ***<u>Cold</u>*** Pour

H3: GSD 745-80-25, Crack Seal ***<u>Hot</u>*** Pour, Type I, Class A

C1: Item 3127, Crack Seal ***<u>Cold</u>*** Pour

H2: GSD 745-80-25, Crack Seal ***<u>Hot</u>*** Pour, Type III, Class B

Figure C.6. Non-Covered test sections in Lufkin District

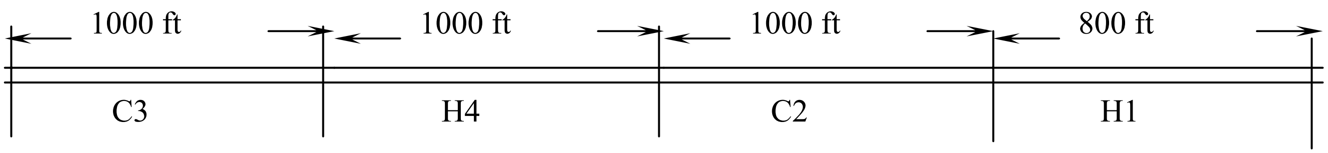
District: Lufkin
County: Polk

Sealing Dates: 2/6/01 and 2/7/01

Highway: US 59

Location: South Bound, Outside Lane

Construction Sequence for Sealants



CODES:

C3: DMS-6310, Class 9, Joint Seal ***Cold*** Pour

H4: DMS-6310, Class 3, Joint Seal ***Hot*** Pour

C2: Item 3127, Crack Seal ***Cold*** Pour

H1: GSD 745-80-25, Crack Seal ***Hot*** Pour, Type I, Class A

Figure C.7. Covered test sections in Lufkin District

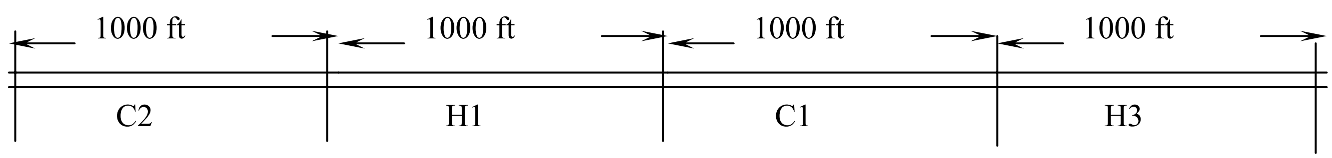
District: Lufkin
County: Polk

Sealing Dates: 2/7/01 and 2/8/01

Highway: US 190

Location: West Bound, Outside Lane

Construction Sequence for Sealants



CODES:

C2: Item 3127, Crack Seal ***Cold*** Pour

H1: GSD 745-80-25, Crack Seal ***Hot*** Pour, Type I, Class A

C1: Item 3127, Crack Seal ***Cold*** Pour

H3: GSD 745-80-25, Crack Seal ***Hot*** Pour, Type I, Class A

Figure C.8. Non-Covered test sections in San Antonio District

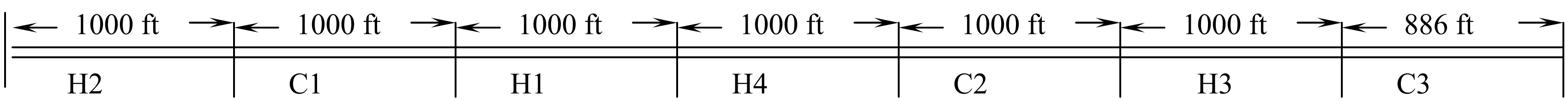
District: San Antonio
County: Bexar

Sealing Dates: 4/25, 4/26, and 4/27/2001

Highway: US 87

Location: North Bound, Outside Lane

Construction Sequence for Sealants



CODES:

C1: Item 3127, Crack Seal ***Cold*** Pour

H1: GSD 745-80-25, Crack Seal ***Hot*** Pour, Type I, Class A

C2: Item 3127, Crack Seal ***Cold*** Pour

H2: GSD 745-80-25, Crack Seal ***Hot*** Pour, Type III, Class B

C3: DMS-6310, Class 9, Joint Seal ***Cold*** Pour

H3: GSD 745-80-25, Crack Seal ***Hot*** Pour, Type I, Class A

H4: DMS-6310, Class 3, Joint Seal ***Hot*** Pour

Appendix D: Performance Evaluations

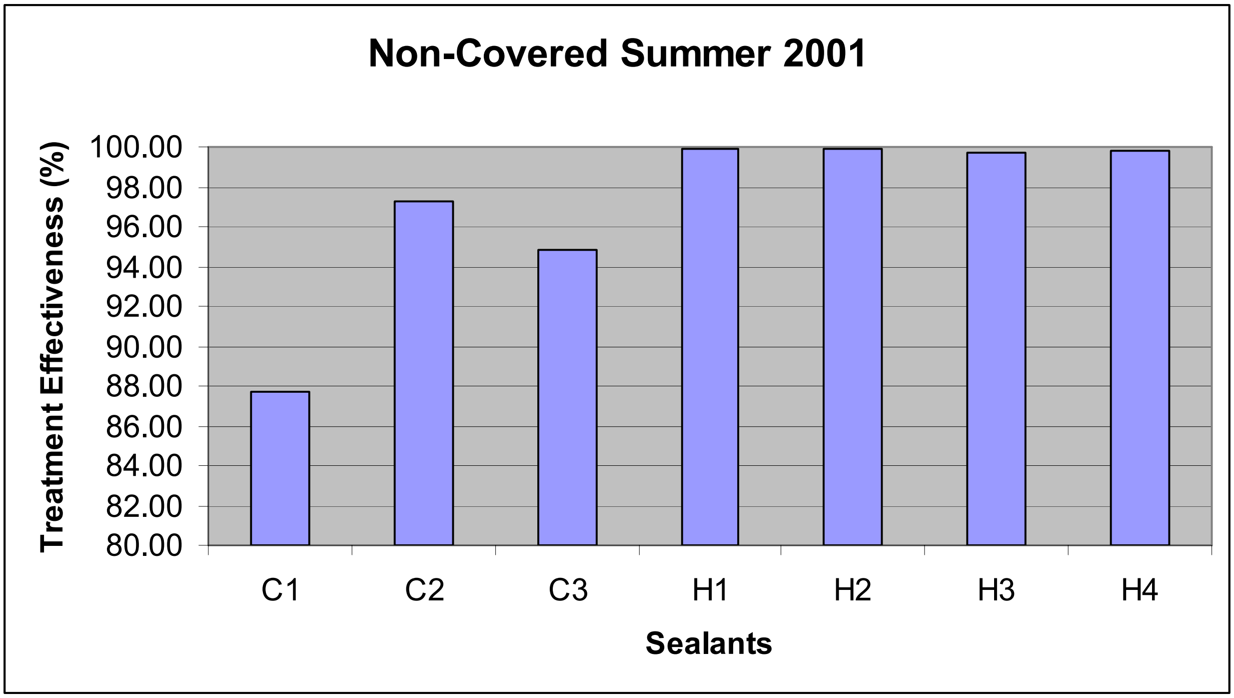


Figure D.1. Overall performance on non-covered test sections in summer 2001

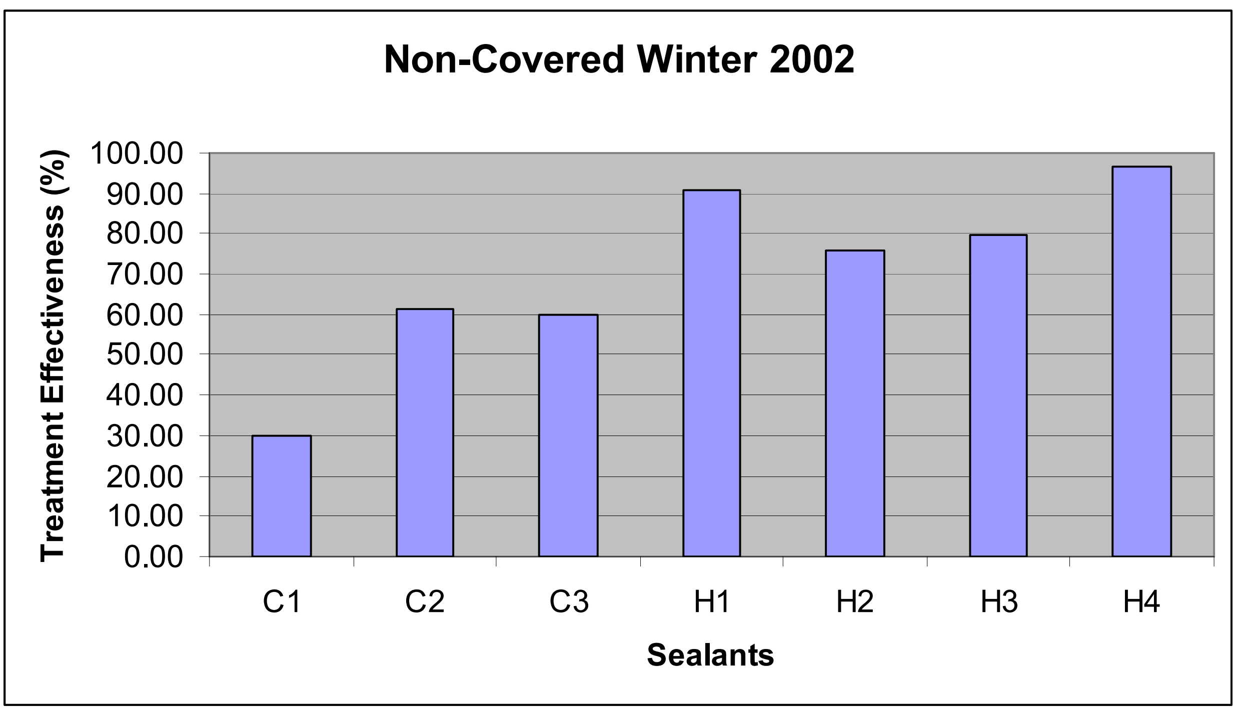


Figure D.2. Overall performance on non-covered test sections in winter 2002

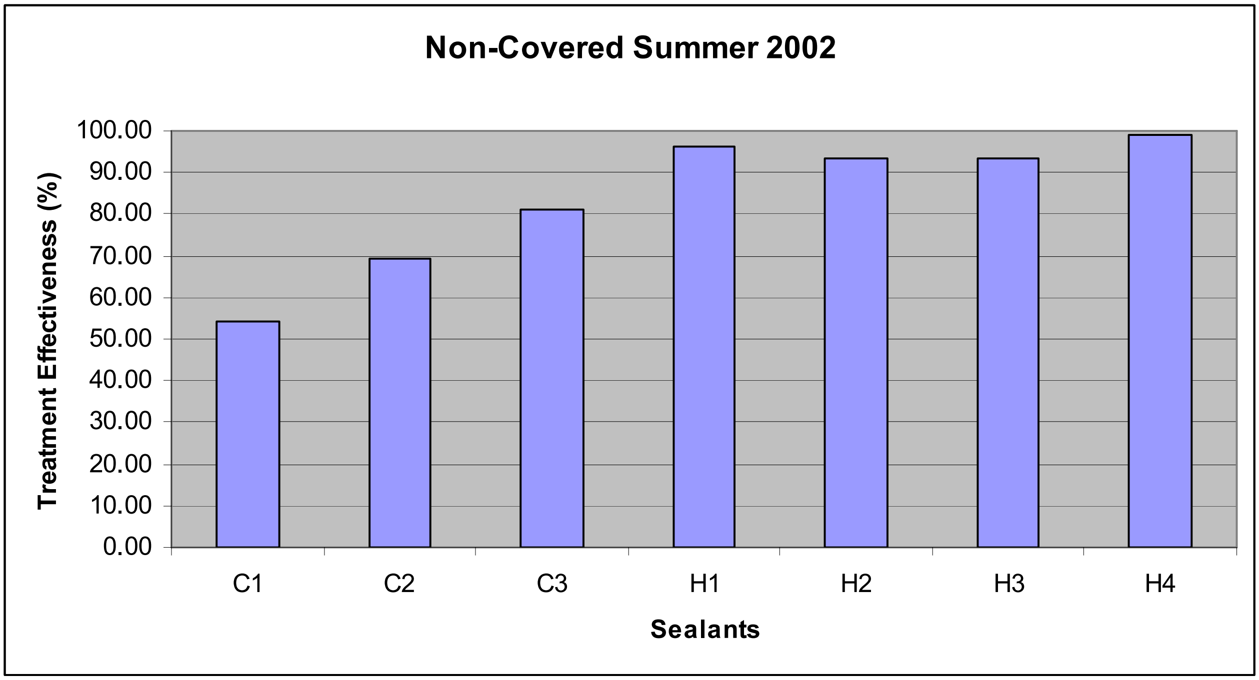


Figure D.3. Overall performance on non-covered test sections in summer 2002

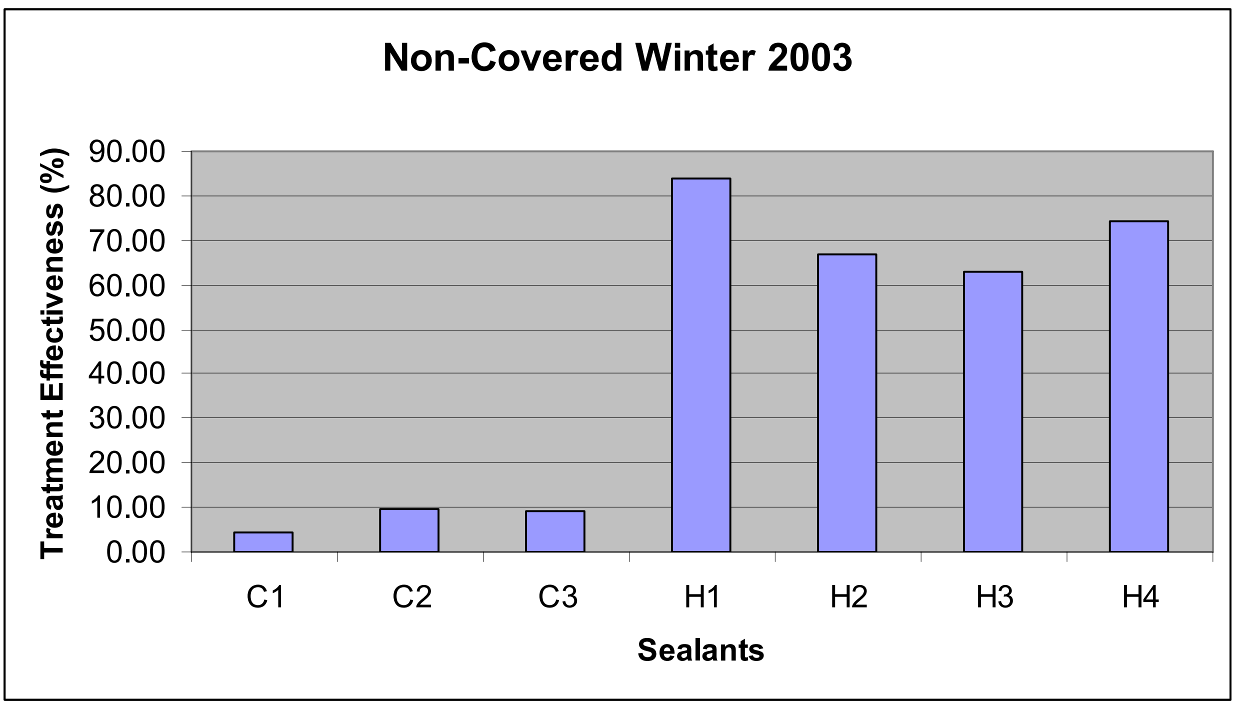


Figure D.4. Overall performance on non-covered test sections in winter 2003

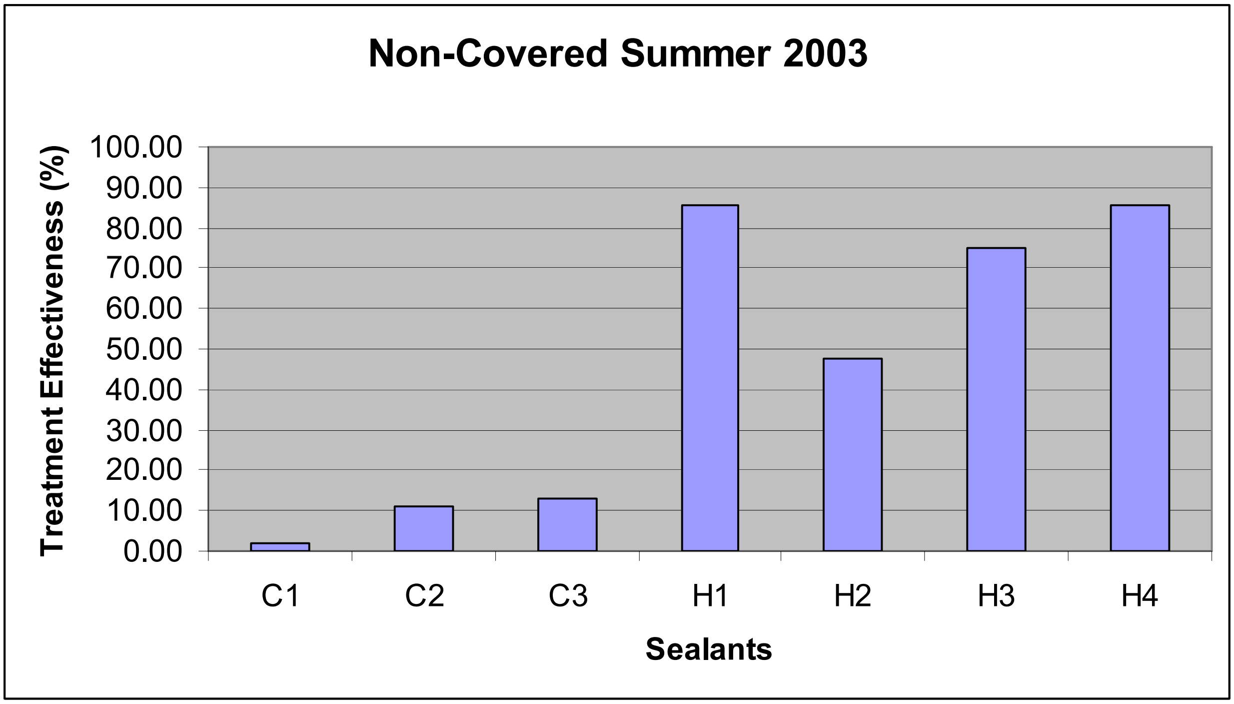


Figure D.5. Overall performance on non-covered test sections in summer 2003

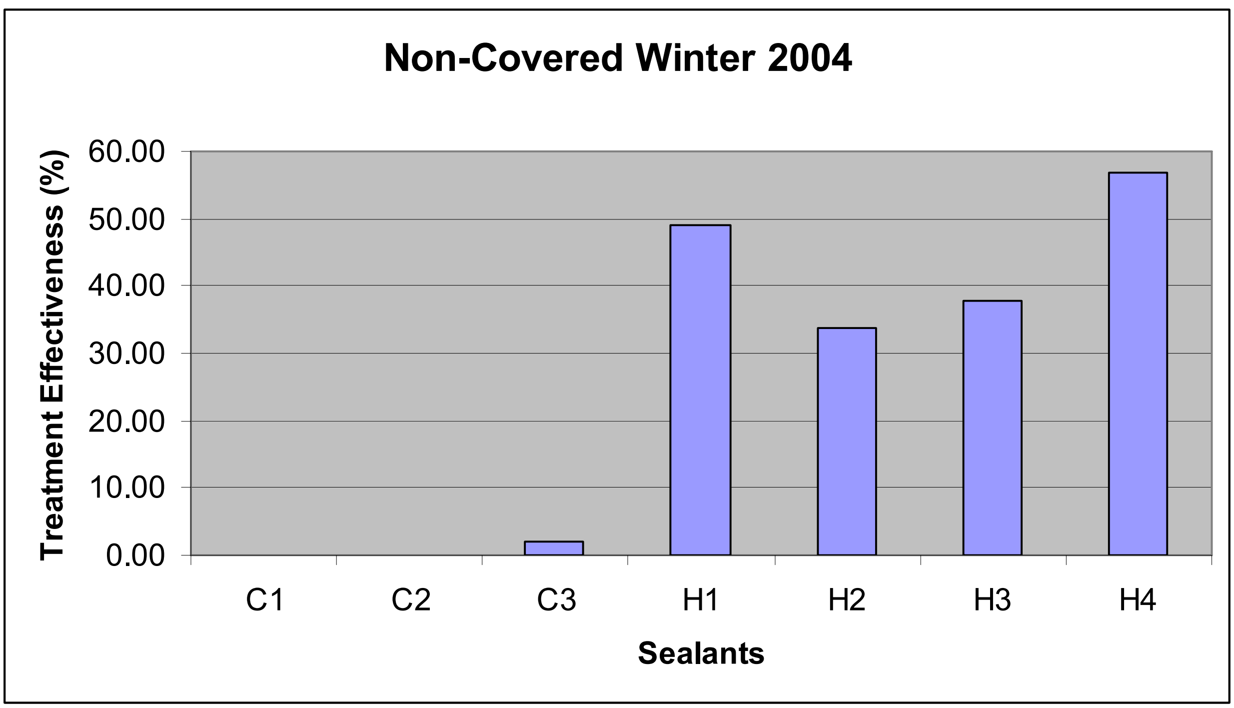


Figure D.6. Overall performance on non-covered test sections in winter 2004

Appendix E: Cost Analysis

Table E.1. Cost-Effectiveness Table for Atlanta

Sealant	Initial Cost for 50,000 ft Imaginary Length ($)	Life (in yrs.)	AAC ($)	AAC ($/ft)
C1	4,419.65	0.927	4992	0.100
C2	4,400.99	0.905	5115	0.102
C3	5,895.86	1.598	3901	0.078
H1	3713.97	4.137	912	0.018
H2	3649.32	3.633	1031	0.021

Table E.2. Cost-Effectiveness Table for El Paso

Sealant	Initial Cost for 50,000 ft Imaginary Length ($)	Life (in yrs.)	AAC ($)	AAC ($/ft)
C1	6,317.58	1.631	4144	0.083
C2	9,179.92	0.811	11401	0.228
H2	6,423.95	2.153	3162	0.063
H3	6,276.01	2.536	2700	0.054

Table E.3. Cost-Effectiveness Table for Amarillo

Sealant	Initial Cost for 50,000 ft Imaginary Length ($)	Life (in yrs.)	AAC ($)	AAC ($/ft)
C1	11,037.83	0.320	35000	0.700
C3	11,061.05	0.691	16300	0.326
H1	9,140.31	2.751	3450	0.069
H3	10,352.95	1.740	6300	0.126
H4	9,438.94	1.927	5150	0.103

Table E.4. Cost-Effectiveness Table for San Antonio

Sealant	Initial Cost for 50,000 ft Imaginary Length ($)	Life (in yrs.)	AAC ($)	AAC ($/ft)
C1	5,031.42	0.489	10443	0.209
C2	4,970.63	1.563	3323	0.066
C3	5,254.48	1.538	3712	0.074
H1	4,484.45	3.281	1461	0.029
H2	6,646.10	0.844	7917	0.158
H3	2,946.79	3.366	950	0.019
H4	5,459.81	3.168	1846	0.037

Table E.5. Cost-Effectiveness Table for Lufkin

Sealant	Initial Cost for 50,000 ft Imaginary Length ($)	Life (in yrs.)	AAC ($)	AAC ($/ft)
C2	5,688.80	1.748	3276	0.066
C3	6,215.87	1.674	3728	0.075
H1	4,666.06	2.787	1707	0.034
H4	5,325.40	3.224	1815	0.036

Table E.6. Average Cost-Effectiveness Values

Sealant	Initial CC for 50,000 ft Imaginary Length* ($)	Average AAC* ($)	Average AAC* ($/ft)	Std Deviation*
C1	5256	6526	0.131	0.068
C2	6060	5779	0.116	0.077
C3	5789	3780	0.076	0.002
H1	4288	1360	0.027	0.008
H2	5573	4037	0.081	0.071
H3	4611	1825	0.037	0.025
H4	5393	1831	0.037	0.000

*In this table, values from Amarillo were not included.