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16. Abstract Crack sealants are widely used in Texas to prevent water from entering into lower structural layers thereby extending pavement life. However, most current crack sealants have been reported to have a very short life mainly due to adhesive failures. Although adhesive failure is known to be the major failure mechanism very little attention has been paid to measuring this property in the laboratory. The main objective of this project was to develop a performance related adhesion test using TxDOT's Overlay Tester. In this report the crack sealant adhesion test protocol developed in year 1 of this study was finalized. The final test protocol includes a molding jig, a detailed sample preparation procedure, an adhesion test protocol, and criteria for interpreting the results. In this study 13 sealants (some of them have never been used in Texas) were evaluated following the proposed test protocol. The results clearly showed that the crack sealant adhesion test can effectively differentiate the poor sealants from the good ones. Furthermore, based on these test results, a draft crack sealant special specification was proposed. This is different from the current specification, which is mainly based on crumb rubber content. The new special specification is based on the results of the new adhesion test. In addition to this performance test other complementary factors such as flash point, softening point, and viscosity have been included in the new specification. In the proposed specification, the sealants are classified as: Type A (min. 100 cycles to failure at 45 °F), Type B (min. 400 cycles to failure at 45 °F), and Type C (min. 400 cycles to failure at 33 °F). In addition, preliminary recommendation on optimum sealant types were made for each district in the state based on climatic conditions (freeze thaw cycles). Finally, an experimental test plan was developed to validate the draft special specification.					
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DEVELOPMENT OF THE CRACK SEALANT ADHESION TEST

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There is no invention or discovery conceived or first reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

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- Jerry Peterson, P.E.
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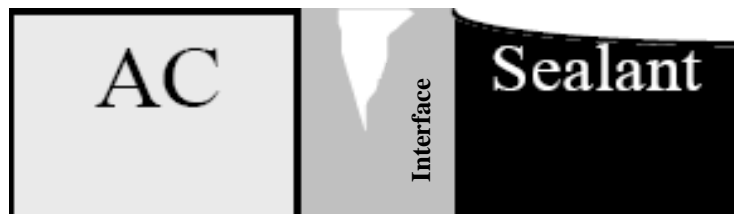
CHAPTER 1

INTRODUCTION

BACKGROUND

Crack sealing is a practice used for routine and preventive maintenance, as well as part of a preservation strategy. The prime function of any crack sealant material is to prevent moisture ingress to the pavement structure. The protection is derived from the reduction of incompressible debris retention in a pavement joint/crack and minimizing the infiltration of water through the pavement joint/crack. Properly installed crack sealant may extend pavement life by several years. Moreover, several studies have shown that crack sealants are cost effective when used to preserve pavements (1-7).

However, crack sealant failures are common within the first few years of service. Major causes of sealant failures can be classified under two categories: 1) adhesion failure, see Figure 1(a), where the interface between sealant and asphalt concrete (AC) or Portland cement concrete (PCC) can no longer sustain the shear and tension forces imposed by the traffic and the pavement contraction that occurs in cold weather; and 2) cohesion failure, see Figure 1(b), where the sealant split within the bulk of the material, but it still adheres to crack walls. Both failures can lead to a significant reduction of service life of the pavement structure. However, the adhesive failure, in most cases, is a dominant failure type (8). Therefore, it is critical to evaluate the potential adhesive failure of crack sealant in the laboratory and select the sealants with better resistance to the adhesive failure.



(a) Adhesion Failure



(b) Cohesion Failure

Figure 1. Crack Sealant Failures: Adhesive and Cohesive Failures.

Existing Laboratory Tests for Characterizing Potential Adhesive Failure of Crack Sealants

Several laboratory tests are currently used to evaluate properties of crack sealants, such as rotational viscosity, penetration, softening point, ductility, and bond tests. Among these tests, the bond test is specifically used to evaluate the adhesive failure of crack sealants, and the procedure of the bond test is well documented in ASTM D5329-04: *Standard Test Methods for Sealants and Fillers, Hot Applied, for Joints and Cracks in Asphaltic and Portland Cement Concrete Pavements* (9). Generally, the bond test takes several days to complete, and the pass/fail criterion is determined through visual observation. Furthermore, the correlation between the bond test and field adhesive failure performance of crack sealants has been found to be either weak or non-existent. Therefore, a simple, fast, and performance-related test is needed to assist the Texas Department of Transportation (TxDOT) to ensure the proper selection of a sealant for a given project.

It is worth noting that during study of TxDOT Project 0-5457, there has also been an ongoing national pooled-fund study TPF-5 (045) with the objective of establishing performance guidelines for the selection of crack sealants (10). The recommendations of this national effort have not been finalized.

Overlay Tester

Crack sealant failure, regardless of adhesive or cohesive failure, is a cracking-related failure. If the weak point is located at the interface of sealant/crack walls of asphalt concrete pavements, an adhesive crack will occur. This type of failure can be easily evaluated by the Texas Transportation Institute (TTI) Overlay Tester.

Initially, the Overlay Tester was designed to evaluate the effectiveness of geosynthetic products on preventing reflective cracking at TTI in late 1970s. The key parts of the Overlay Tester, as shown in Figure 2, consist of two steel plates, one fixed and the other movable horizontally to simulate the opening and closing of joints or cracks in the old pavements beneath an overlay.

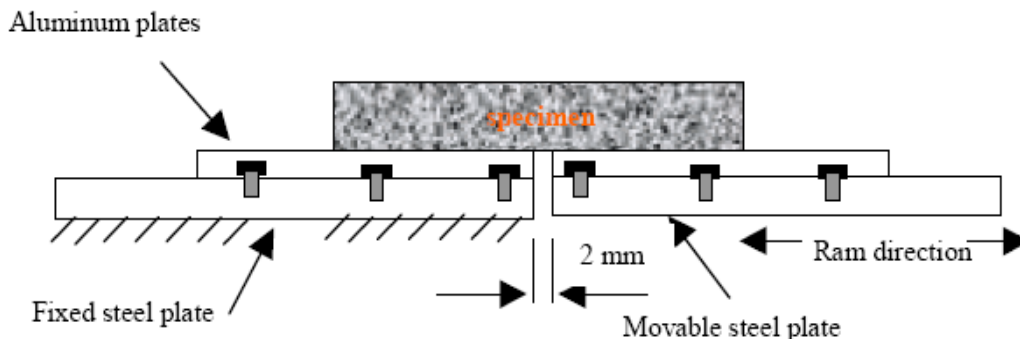


Figure 2. Concept of the TTI Overlay Tester.

In the past six years, the TTI Overlay Tester has been completely upgraded and the most recent Overlay Tester is shown in Figure 3. All the upgraded Overlay Testers

are fully automated and computer controlled systems with an additional temperature-control chamber in which the temperature can vary from 95 °F to 23 °F. Also, the upgraded Overlay Tester has been well validated for evaluating crack resistance of hot-mix asphalt (HMA) mixes under TxDOT Research Projects 0-4467, 0-5123, and other projects. The crack-related failures, such as reflective, fatigue, and low temperature cracking, can be easily and effectively evaluated using the upgraded Overlay Tester. This test has been approved by TxDOT, and now a draft test procedure Tex-Method 248 – F has been approved for use for HMA evaluation.

For crack sealants both adhesive and cohesive failures are thermally related, which is the exact failure mechanism simulated in the Overlay Tester. Thus, it is feasible and logical to use the Overlay Tester to evaluate these potential failure mechanisms.

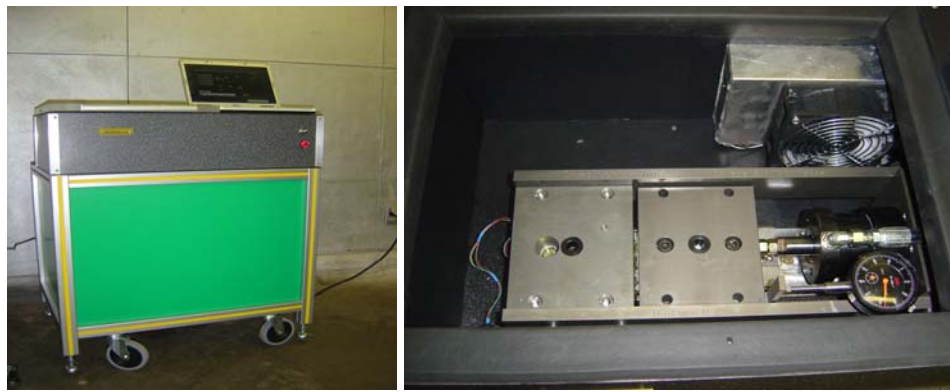


Figure 3. TTI Overlay Tester.

OBJECTIVES

The overall objectives of this project were to:

- (1) Develop the crack sealant test protocol.
- (2) Test and evaluate 13 sealants from vendors.
- (3) Recommend a draft specification for sealant acceptance.

REPORT ORGANIZATION

This report is organized into five chapters. [Chapter 1](#) provides brief background information relative to the project. [Chapter 2](#) introduces the development of the crack sealant adhesion test using the Overlay Tester and associated test protocol. [Chapter 3](#) describes the crack sealant tests on the 13 sealants from vendors. The test results and associated analysis are also presented in [Chapter 3](#). Based on these test results, a draft crack sealant specification is presented and discussed in [Chapter 4](#). Finally, [Chapter 5](#) presents a summary of conclusions and recommendations for this project.

CHAPTER 2

DEVELOPMENT OF THE CRACK SEALANT ADHESION TEST

INTRODUCTION

This chapter describes development of an Overlay Tester-based crack sealant adhesion test. First, the TTI Overlay Tester is briefly described. Then, the crack sealant adhesion test protocol is discussed. Finally, the repeatability and sensitivity results for the crack sealant adhesion test are presented.

TTI OVERLAY TESTER

The TTI Overlay Tester was originally designed by Lytton and his associates (11) in the late 1970s to simulate the opening and closing of joints or cracks. The key parts of the apparatus consist of two steel plates, one fixed and the other movable horizontally to simulate the opening and closing of joints or cracks in the old pavements beneath an overlay. The Overlay Testers have been successfully used by Pickett and Lytton (12), Button and Epps (13), Button and Lytton (14), and Cleveland et al. (15) to evaluate the effectiveness of geosynthetic materials on retarding reflection cracking. Most recently, Zhou et al. (16, 17, 18, 19, 20) have successfully used the Overlay Tester to evaluate the reflection, thermal, and fatigue crack resistance of HMA mixes in Texas.

Additionally, an independent study conducted by Bennert and Maher, Rutgers University, further confirmed that the Overlay Tester is a simple performance test for reflection cracking (21). In October 2006, a two-layer HMA overlay (38 mm thick 9.5 mm Superpave mix with PG76-22 binder plus 75 mm thick 12.5 mm Superpave mix with PG76-22 binder) was constructed over existing PCC pavements in New Jersey. Both mixes were tested under the Overlay Tester. The Overlay Tester cycles to failure are 23 cycles for 12.5 mm Superpave mix and 82 cycles for 9.5 mm Superpave mix. Based on TTI's experience and other information such as climate and load transfer efficiency, it was predicted that this two-layer HMA overlay would fail within one year. As shown in Figure 4, reflection cracks observed in March 2007 were observed after a prolonged cold spell and they extend across the entire surface.

Since crack sealant failure is crack-related failure, it is feasible and logical to use the Overlay Tester to evaluate the potential field failure of crack sealants. The main difference is that the crack sealants, compared to HMA mixes, are much softer and very flexible, even in relatively cold temperatures. Therefore, a larger opening displacement and colder temperature are required when testing crack sealants using the Overlay Tester.



Figure 4. Reflection Cracking in Route 34 NB, New Jersey (21).

CRACK SEALANT ADHESION TEST

The Loading Conditions

The thermal movements acting on HMA overlays placed over jointed concrete pavements are influenced by many factors, such as the temperature cooling rate, thermal coefficients of expansion, and other factors. Also, the movement is very slow and often lasts several hours. It is ideal to apply the true maximum opening movement with the sample slow loading/unloading rate in the lab to simulate what happens in the field, which, however, is impractical because of the lengthy testing time. The thermal movements experienced by crack sealants are of the same magnitude and duration as those experienced by HMA overlays.

Based on a series of trials, the experience with testing HMA mixes, and the need to have a test which can be completed in a reasonable amount of time the following loading conditions are recommended for the crack sealant test:

- maximum opening movement (or displacement): 0.1 inches.
- loading/unloading time: 5 seconds loading plus 5 seconds unloading time (10 seconds per cycle). Within 3 hours, 1000 cycles can be applied to the crack sealant.

Failure Definition

The Overlay Tester for HMA concrete is a fixed displacement test, where the load to move the sample a fixed distance is measured in each cycle. Failure of the sample is defined based on the drop in required load. Current HMA failure is defined when the load drops to less than 7 percent of the load measured on the first opening cycle.

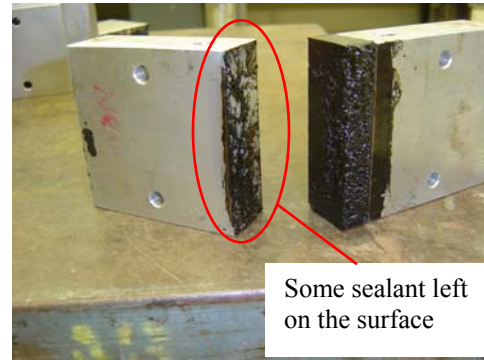
Similarly, for crack sealant test the increase in interface damage between the crack sealant and the mold will cause the load per cycle to drop. It was often visually observed that after a certain amount of load drop from the first maximum load, the test specimen shows complete adhesive failure. Based on numerous crack sealant test results and visual observations, an 80 percent load drop from the maximum tension load measured in the first opening cycle was selected as the failure criterion for the crack sealant test.

Adhesive Failure Types

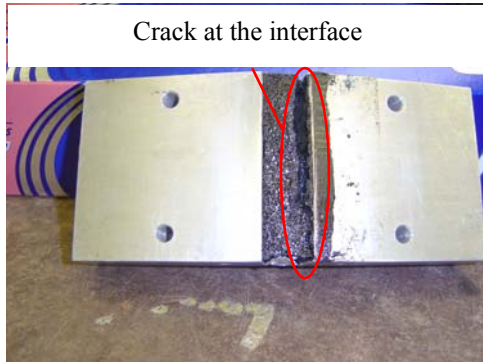
Four adhesive failures as shown in Figure 5 have been observed during the crack sealant test. The most commonly observed adhesive failure is shown in Figure 5a. Its main feature of the type of failure is that one side of the mold is clean, and no sealant is left on the surface of the block. Figure 5b shows the partial adhesive failure where some sealant is still left on the surface of the block. For sealants which perform well in this test only minor adhesive failure (Figure 5c) is observed at the end of testing (typically 2000 cycles), and most of the interface between the sealant and the mold surface is still bounded together. In some cases, after a long testing time, no adhesive failure can be observed, as indicated in Figure 5d.



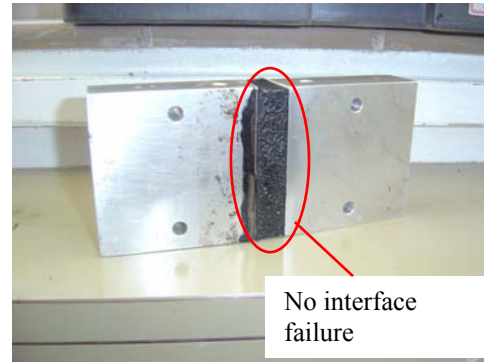
a) Typical adhesive failure



b) Partial adhesive failure



c) Minor adhesive failure



d) No adhesive failure

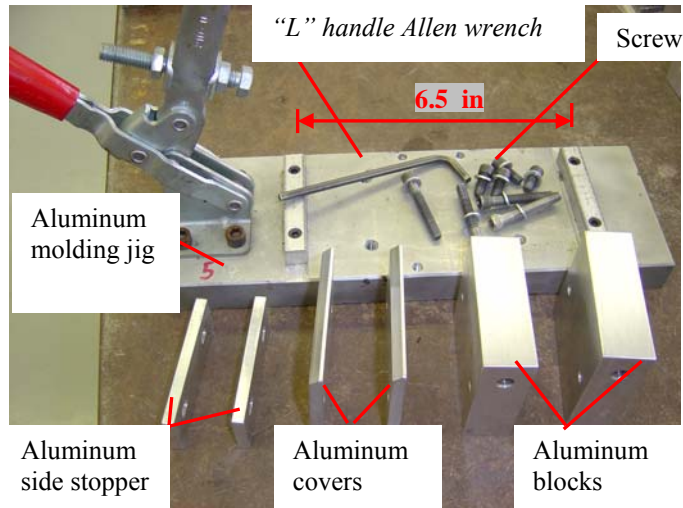
Figure 5. Four Typical Adhesive Failure Types.

CRACK SEALANT MOLD

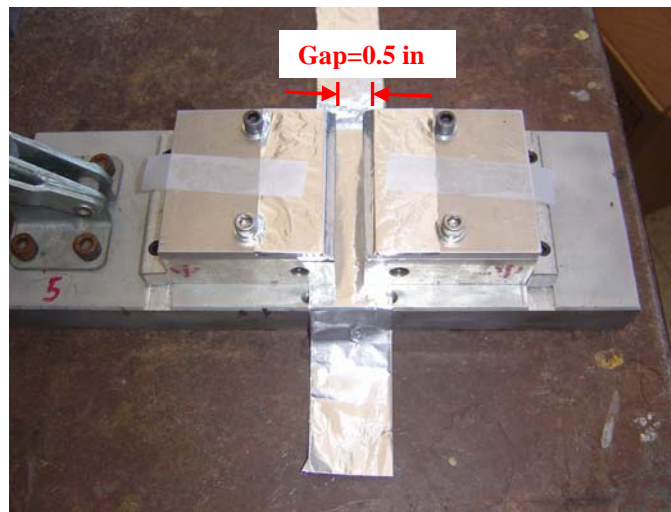
In the initial part of this study the mold used was a cement sand mortar. Two main problems were found with the mortar mold. The first problem was that the mortar mold can be used only once, which means that the mortar mold itself has to be molded first before molding the crack sealant specimen. Another problem with the mortar mold was that the surface uniformity of the mortar molds varied between different molds, which led to significant test variability. To solve these problems, the aluminum mold was

finally selected. The aluminum mold is not only re-usable, but the same uniform surface of the mold can also be manufactured thereby improving the test repeatability.

Additionally, a sealant molding jig and some other accessories were developed in order to mold a consistent crack sealant specimen. As shown in Figure 6a, the crack sealant mold equipment includes an aluminum molding jig, two aluminum side stoppers, two aluminum covers, two aluminum blocks, and screws. A final assembled sealant mold is shown in Figure 6b, where the aluminum foil is used to prevent the sealant sticking to the side stopper and covers. Note that the net distance between two bars of the molding jig is 6.5 inches (Figure 6a), and the two aluminum blocks are 3 inches by 3 inches so that the 0.5 inch gap between the two aluminum blocks (Figure 6a) is guaranteed.



(a) Components of Crack Sealant Mold



(b) Assembled Crack Sealant Mold

Figure 6. Crack Sealant Mold.

STEP BY STEP MOLDING PROCESS OF CRACK SEALANT SPECIMEN

After assembling the crack sealant mold and sampling the crack sealant from the crack sealant box using a drill, the crack sealant specimen can be molded using the following steps: (note that a more detailed explanation is provided in test protocol shown in the [Appendix](#))

Step 1: Heat the Sampled Sealant.

Set the oven temperature to the sealant melting temperature recommended by the manufacturers. Put the sampled sealant in a bowl and one spoon into the oven. Wait 2 hours before starting to mold. Meanwhile, set the conditioning chamber temperature to the test temperature 41 °F (5 °C). The melting crack sealant needs to be stirred twice during this heating period.

Step 2: Mold Sealant Specimen.

After a 2 hour heating stir and pour the melted sealant into the sealant mold as quickly as possible, meanwhile, vibrate the sealant molding jig 20 times by hand. Finish this process as quickly as possible because the sealant temperature drops very quickly. Vibrate the sealant molding jig with hands in order to shake the air out of the mold. Additionally, after pouring and vibrating; allow the sealant to cool down (around 3 min.) before removing the molding jig. Just after pouring the melted sealant into the mold, place the sealant back to the oven. Wait 5 min. and then begin molding the next specimen. Repeat this process until five sealant specimens are molded.

Step 3: Trim Sealant Specimens.

Trim the sealant specimen using the hot putty knife scraper 40 minutes after molding. Keep the blade of the putty knife horizontal when trimming the sealant, remove all of the sealant from the top of the blocks. After trimming, cover the sealant surface with aluminum foil.

Step 4: Store Sealant Specimens.

After trimming five sealant specimens, place all of the sealant specimens in the environmental chamber of 41 °F (5 °C) and keep them there at least 2 hours before moving them into the crack sealant tester. Meanwhile, about 1 hour after the sealant specimens are placed in the environmental chamber, peel off all of aluminum foil quickly from the sealant surface, and then wrap up every sealant specimen using new aluminum foil. The purpose of doing so is to make removal of the aluminum foil easy when clamping the sealant specimens down to the crack sealant tester.

CRACK SEALANT ADHESION TEST PROTOCOL

After the crack sealant specimen(s) are prepared, the crack sealant adhesion test can be conducted following the steps below. Note that the detailed test protocol is presented in the [Appendix](#) at end of this report.

Step 1: Start Crack Sealant Tester.

Turn on the crack sealant tester and open the software by double clicking “overlay.exe,” and set up the target test temperature.

After the temperature in the air bath chamber of the crack sealant tester reaches the target test temperature, take all of sealant specimens out of the environmental chamber, and then load them immediately into the crack sealant test chamber. The sealant specimens should be conditioned within the test machine at the target test temperature overnight or at least 8 hours, so that the temperature of the whole sealant specimen is uniform and stable.

After loading the sealant specimens into the chamber of the crack sealant tester, the operator needs to set up several test parameters including “Max opening displacement”; “load drop”, “Loading/Unloading Time”, “Number of cycles”, and fill in the information of the test sample, such as “Project Name”, “Specimen ID\Lab”, “Technician’s Name”, “Data File Name”, and “Test Remarks”, as shown in [Figure 7](#). The machine must show “Pump On” status under the “Displacement” control mode.

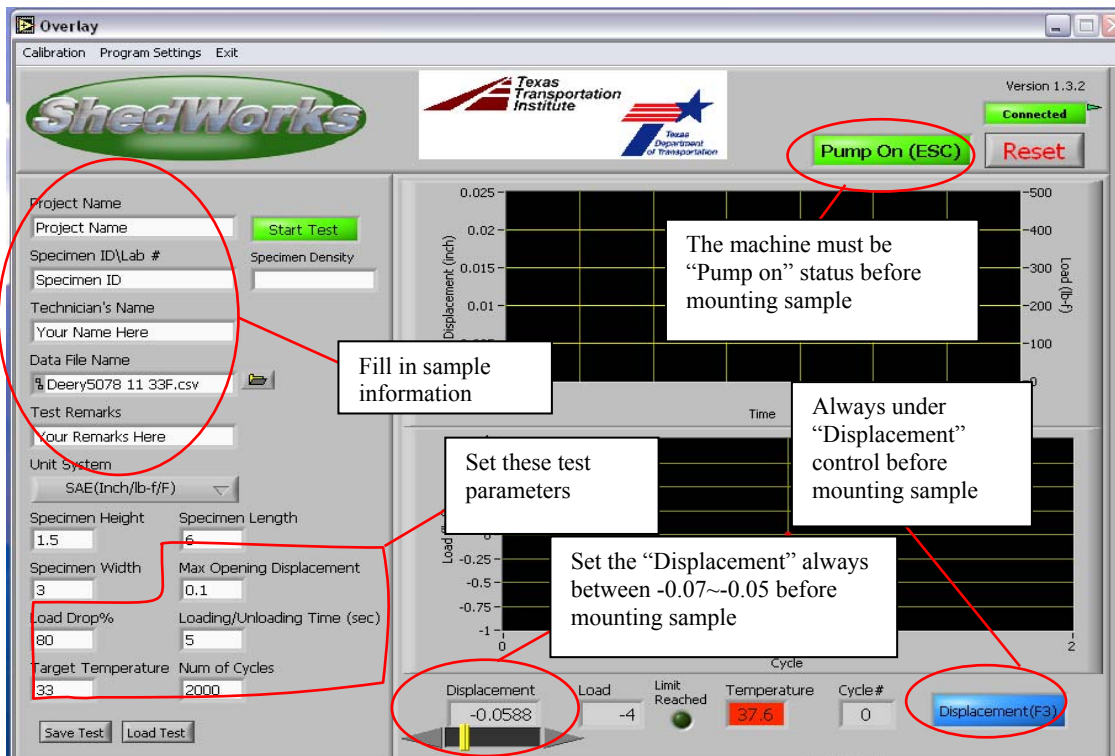


Figure 7. Main Screen of Crack Sealant Tester.

Step 2: Clamp the Sealant Specimen.

Clamp the sealant specimen down to the crack sealant tester using the clamps shown in [Figure 8](#). Complete this process as quickly as possible in order to limit the temperature change of the sealant specimen. Center the sealant specimen between the two clamps.

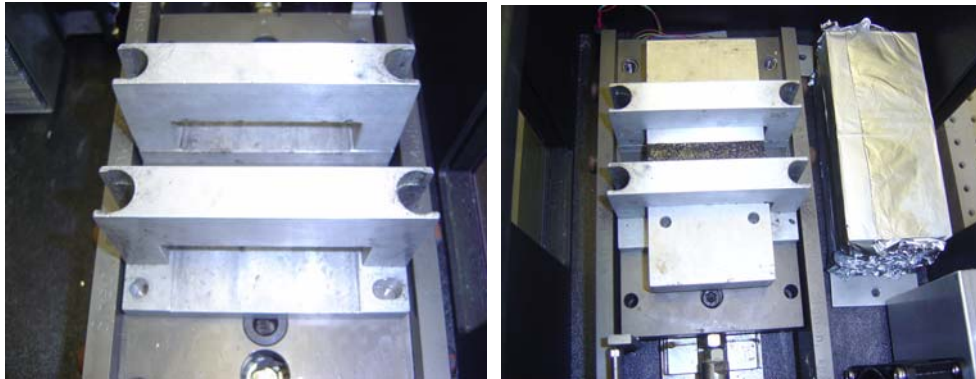


Figure 8. Crack Sealant Clamp and Clamped Test Specimen.

Step 3: Run the Crack Sealant Adhesion Test.

At least 1 hour after clamping the crack sealant specimen, press the “Start Test” button in the main screen of the crack sealant tester ([Figure 7](#)) to begin the test. The purpose of waiting for 1 more hour is to make sure that the temperature of the sealant specimen reaches the target test temperature again, because in most cases, crack sealants are very temperature sensitive.

Step 4: Stop the Crack Sealant Adhesion Test.

There are two stop criteria in the crack sealant tester. First, the test will stop automatically when the data recorded in the software reach the 80 percent load drop from the maximum load at the first cycle, which is defined as the adhesive failure criterion. Additionally, the test will stop when the running cycles reach the maximum number of cycles the operator sets ([Figure 7](#)).

Step 5: Report the Test Results.

The test data are automatically recorded in the computer during testing. After finishing the test, report the following items: (1) test temperature; (2) the percentage of load drop; (3) the maximum load of first cycle; (4) number of cycles to the adhesive failure (or 80 percent load drop); and (5) adhesive breaking condition (shown in [Figure 5](#)).

In summary, this chapter documented the developed crack sealant test protocol. The test results of 13 sealants following the proposed test protocol are presented in the next chapter.

CHAPTER 3

CRACK SEALANT TEST RESULTS AND ANALYSIS

INTRODUCTION

Current crack sealants are classified as either Class A or Class B in Texas, mainly depending on crumb rubber content. It is worth noting that Class A sealants, most often used in Texas, are specifically produced for Texas and these are not used by any other DOT. During a project meeting with sealant vendors it was claimed that the sealants used by other DOT's are better than those Texas currently uses. To evaluate the vendors' claim the TTI researchers used the crack sealant adhesion tester to evaluate 13 sealants donated from four vendors. The 13 sealants are marked as Sealants A, B, C, D, E, F, G, H, I, J, K, L, and M. Detailed crack sealant adhesion tests and associated results are presented in this chapter.

CRACK SEALANT ADHESION TEST

The crack sealant adhesion tests were conducted following the test protocol proposed in [Chapter 2](#). Specifically, the test parameters or conditions listed below were followed:

- No. of replicates: 5
- Maximum opening displacement: 0.1 inches
- Loading rate: 10 sec. per cycle (5 sec. loading time + 5 sec. unloading time)
- Sealant specimen size: 3 inches long by 1 inches high by 0.5 inches wide
- Adhesive failure definition: 80 percent load drop from the max. load of first cycle
- Maximum test cycles: 2000

No adhesive failure could be observed for some sealants. If this is the case, the test was stopped after 2000 cycles, which took more than 5 hours and 30 minutes.

- Test temperatures: varying from 33 °F to 51 °F

For this research, the test was first conducted at 45 °F. If the number of cycles at 45 °F is greater than 2000, then run the test again at 41 °F, if it last more than 2000 then repeat the test at 37 °F and 33 °F. If the number of cycles at 45 °F is less than 2000, then raise the test temperature at 2 °F or 4 °F intervals and test it again. The goal was to determine the test temperature for each sealant at which it would last a minimum of 2000 cycles to failure.

TEST RESULTS AND ANALYSIS

The test results for the 13 sealants at different temperatures are presented in Figures 9 to 21.

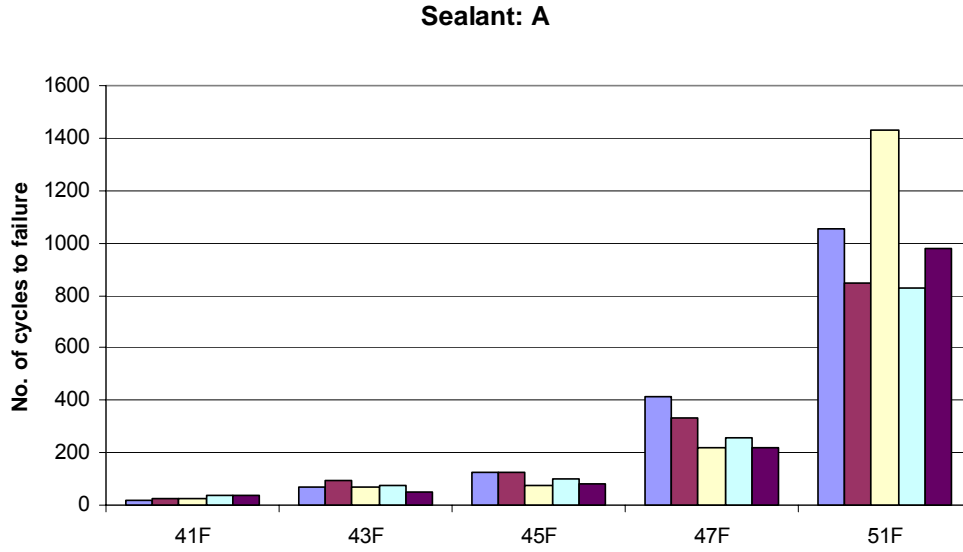


Figure 9. Crack Sealant Adhesion Test Results: Sealant A.

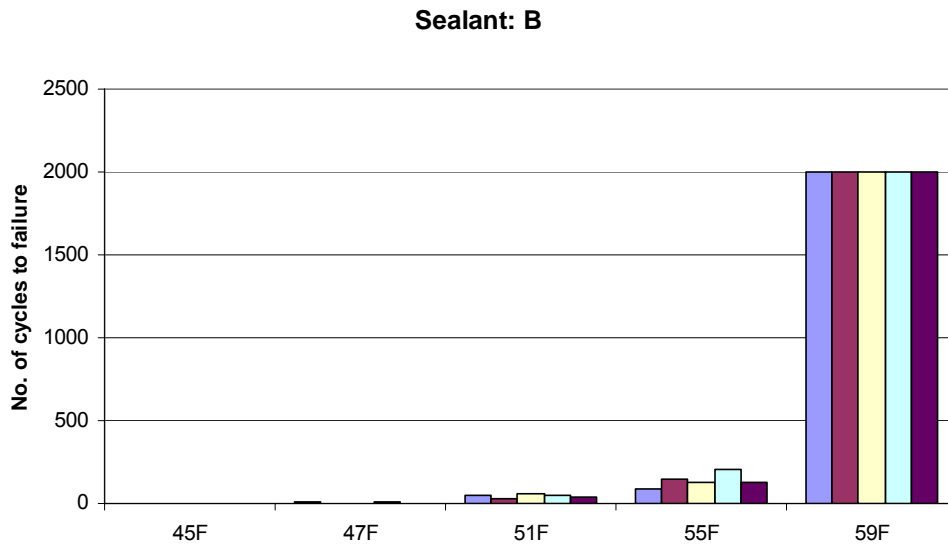


Figure 10. Crack Sealant Adhesion Test Results: Sealant B.

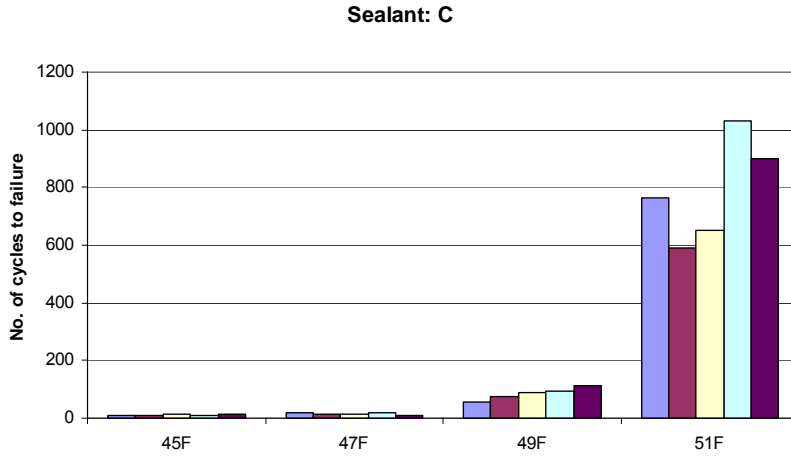


Figure 11. Crack Sealant Adhesion Test Results: Sealant C.

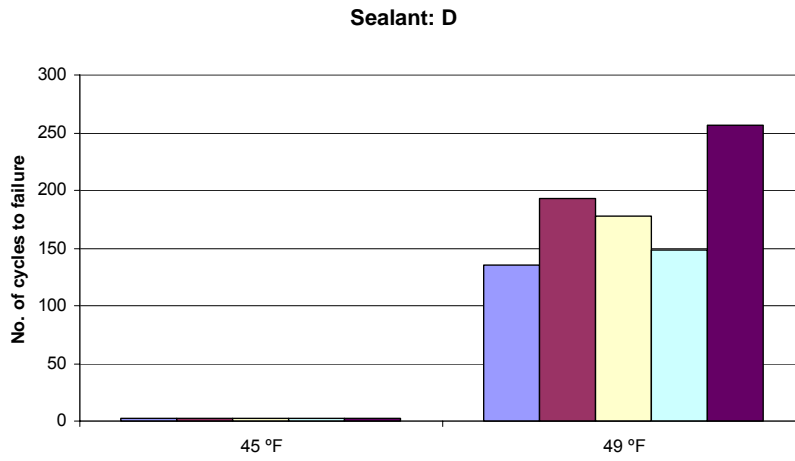


Figure 12. Crack Sealant Adhesion Test Results: Sealant D.

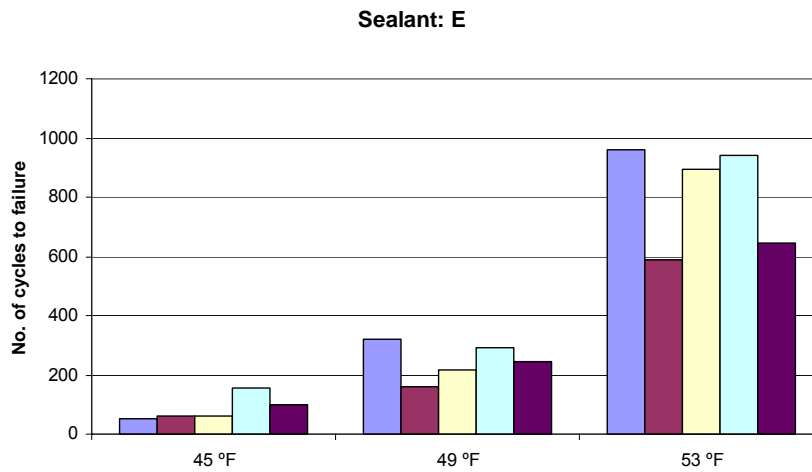


Figure 13. Crack Sealant Adhesion Test Results: Sealant E.

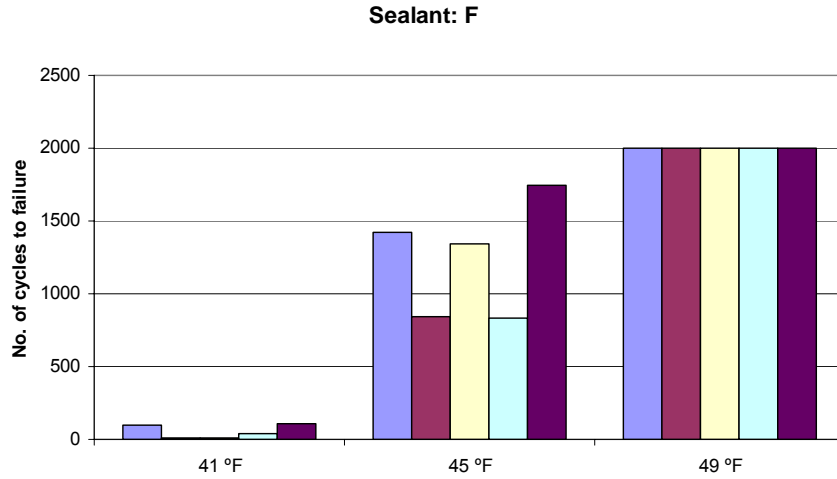


Figure 14. Crack Sealant Adhesion Test Results: Sealant F.

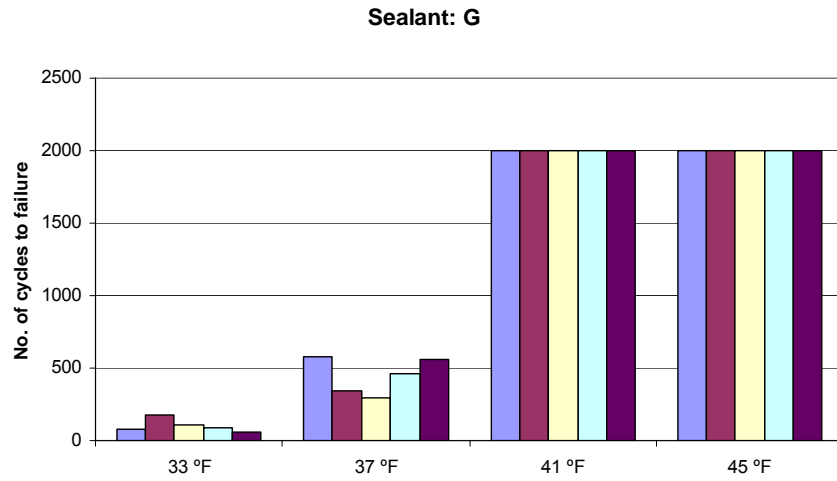


Figure 15. Crack Sealant Adhesion Test Results: Sealant G.

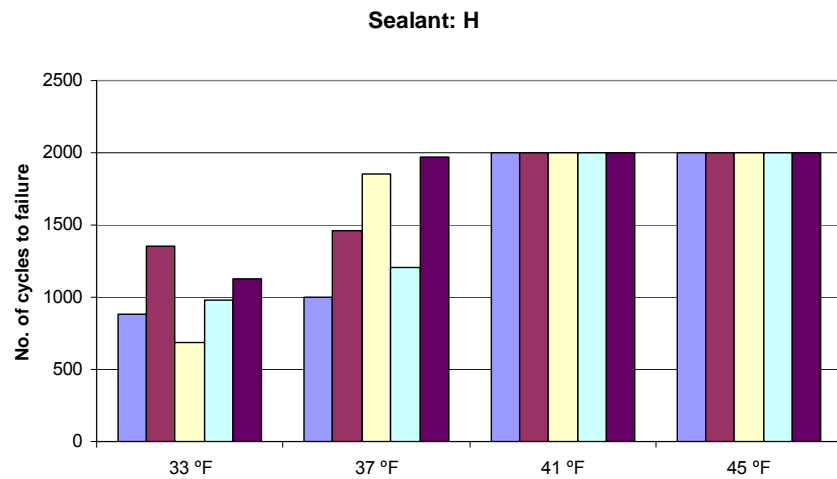


Figure 16. Crack Sealant Adhesion Test Results: Sealant H.

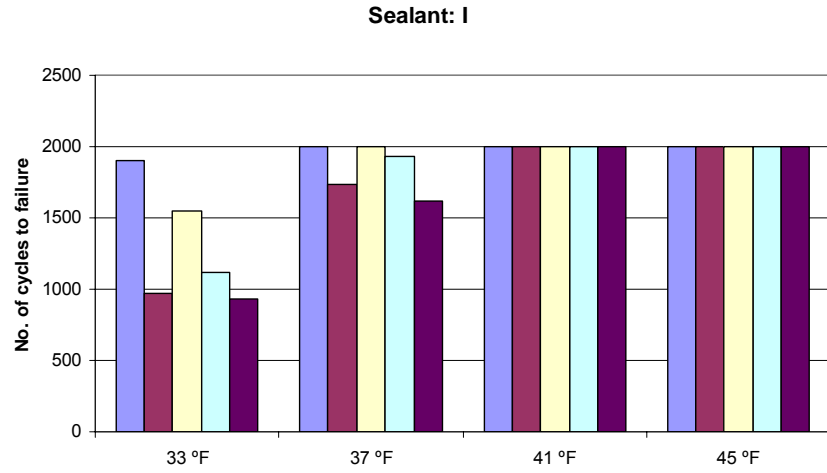


Figure 17. Crack Sealant Adhesion Test Results: Sealant I.

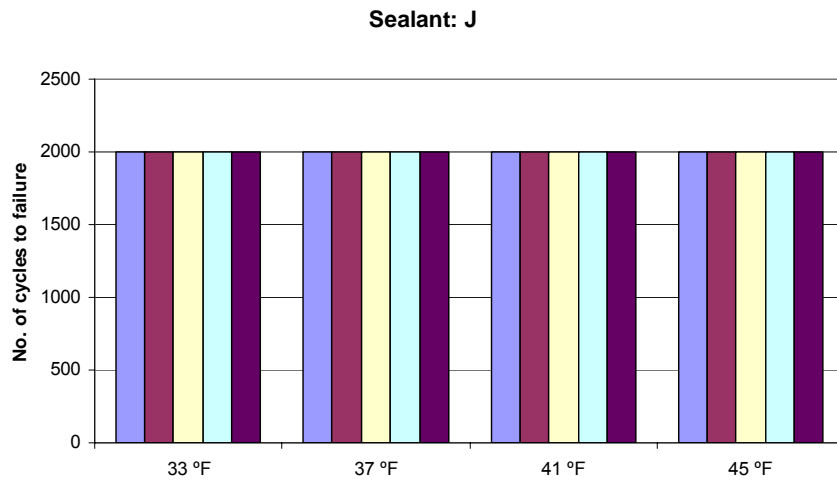


Figure 18. Crack Sealant Adhesion Test Results: Sealant J.

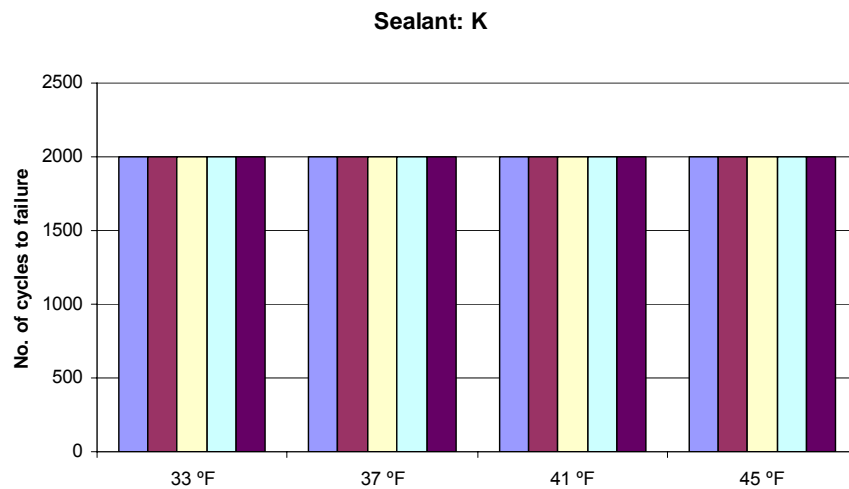


Figure 19. Crack Sealant Adhesion Test Results: Sealant K.

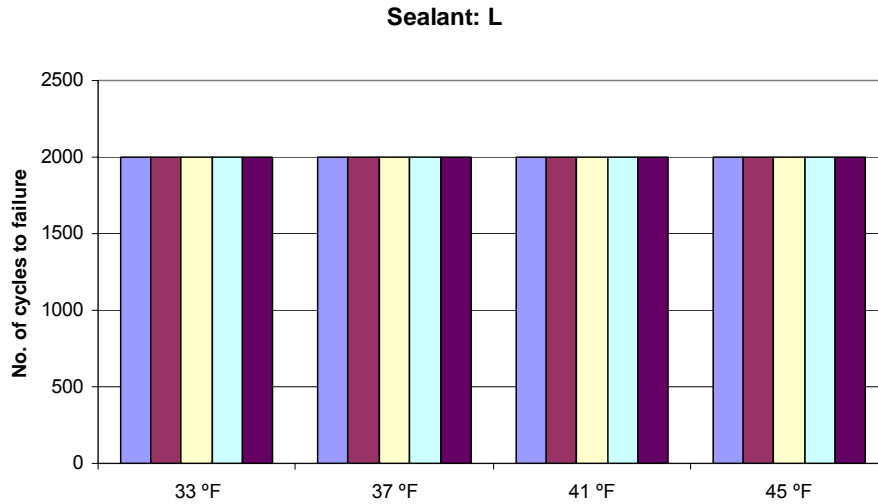


Figure 20. Crack Sealant Adhesion Test Results: Sealant L.

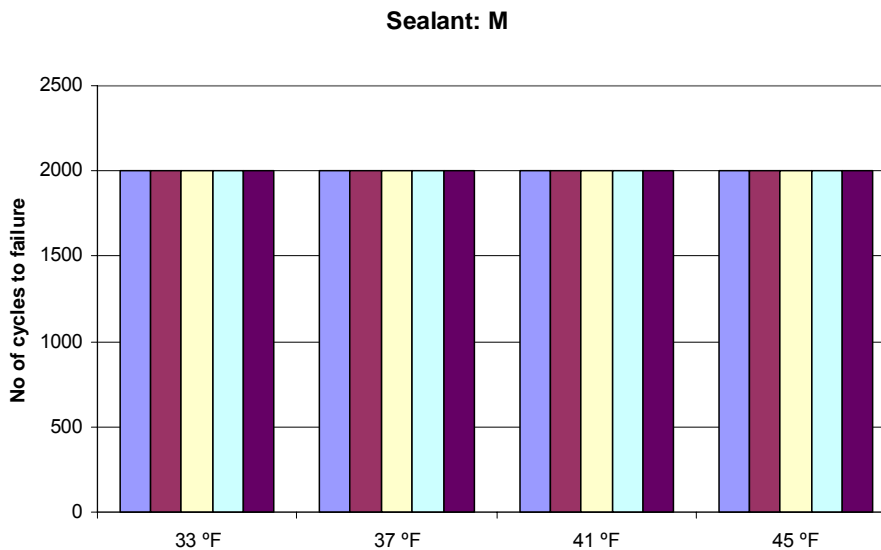


Figure 21. Crack Sealant Adhesion Test Results: Sealant M.

Based on the results presented in [Figures 9-21](#), several observations have been made:

1. In general, the crack sealants are very temperature sensitive. Each sealant has its own “favorite” temperature. When the temperature is below that temperature, the sealant will experience severe adhesive failure. For example, the “favorite” temperature of Sealant B is 59 °F, as shown in [Figure 10](#). This observation indicates that different sealants should be used in different temperature zones, which means that the sealants performing well in the warmer areas of South Texas may not be suitable for the colder temperature conditions in the Texas panhandle. From a review of these data clearly there

is a wide range of performance. This information can be used to select the optimum sealant for each District based on their environmental (winter) conditions.

2. The 13 sealants evaluated in this study can be simply divided into two large groups based on test results at 45 °F, as shown in [Figure 22](#).
 - Group A including Sealants A, B, C, D, and E: These five sealants failed quickly under the adhesion test. Note that Sealants A and B are rubber-based Texas Class A sealants. Sealants C, D, and E have not been tried in Texas.
 - Group B including Sealants F, G, H, I, J, K, L, and M: Compared to Group A, Group B sealants have significantly better adhesion performance. Among these sealants, only Sealant M (Texas Class B) has been used in Texas. Note that Sealants G, H, I, J, K, L, and M did not show any adhesive failure after 2000 cycles.

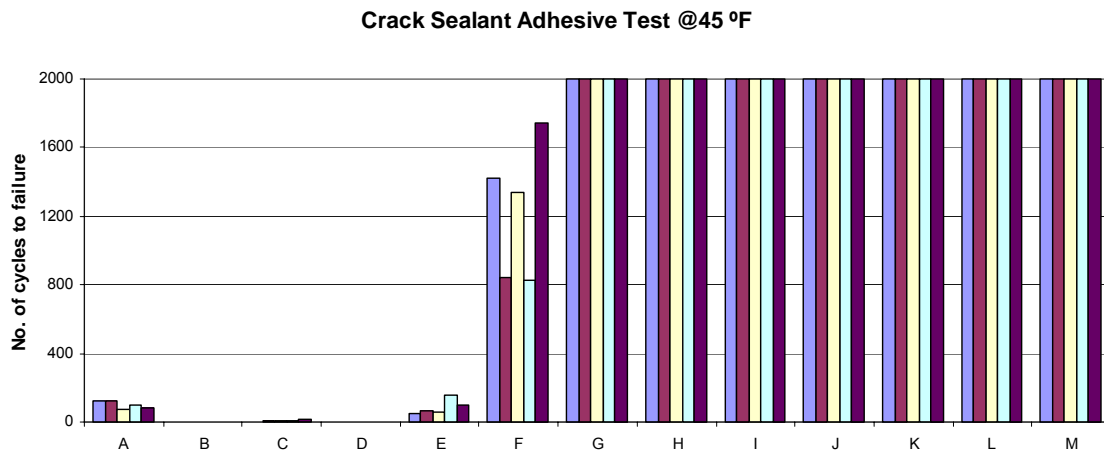


Figure 22. Crack Sealant Adhesion Test Results of the 13 Sealants at 45 °F.

3. If further classification on Group B sealants is needed, test results at 33 °F should be reviewed. As shown in [Figure 23](#), Group B can be further divided into three subgroups:
 - Group B-1: Sealants F and G. These two sealants had adhesive failure with a small number of cycles.
 - Group B-2: Sealants H, I, and M. These three sealants required many more cycles to reach adhesive failure.
 - Group B-3: Sealants J, K, and L. These three sealants were very soft and had no adhesive failure.

However, it should be noted that concerns were raised that these may be too soft for Texas summer conditions; these very soft sealants could potentially stick to the tires and be pulled out from the cracks. These

sealants clearly need to be field tested in limited trials before they can be widely used.

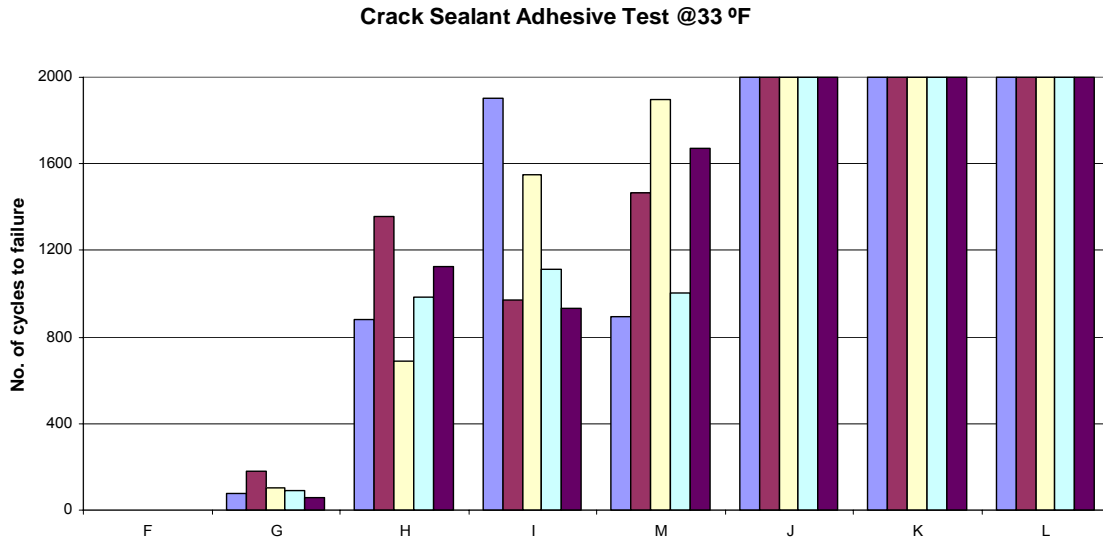


Figure 23. Crack Sealant Test Results of Group B Sealants at 33 °F: No. of Cycles.

4. As noted above, to perform well in the field the sealants need to have a balanced performance: soft in the wintertime and not too soft in the summertime. To avoid too soft sealants in the summer time, one potential parameter is the maximum load of the crack sealant adhesion test at the first cycle. Generally, the maximum load measured at the first cycle indicates how soft or stiff the crack sealant is. The higher the maximum load, the stiffer the crack sealants. [Figure 24](#) shows the maximum load at the first cycle for all 13 sealants measured at 45 °F. It is proposed that until further field studies are completed that tentatively 100 lb can be used as a criterion to evaluate whether or not the sealants are too soft for Texas hot weather. That would eliminate sealants J, K and L from consideration each lasted over 2000 cycles at 33 °F, but were judged to be very soft. The best candidates for good cold weather performance would be sealants I and M.

Crack Sealant Adhesive Test: Max. Load@45 °F

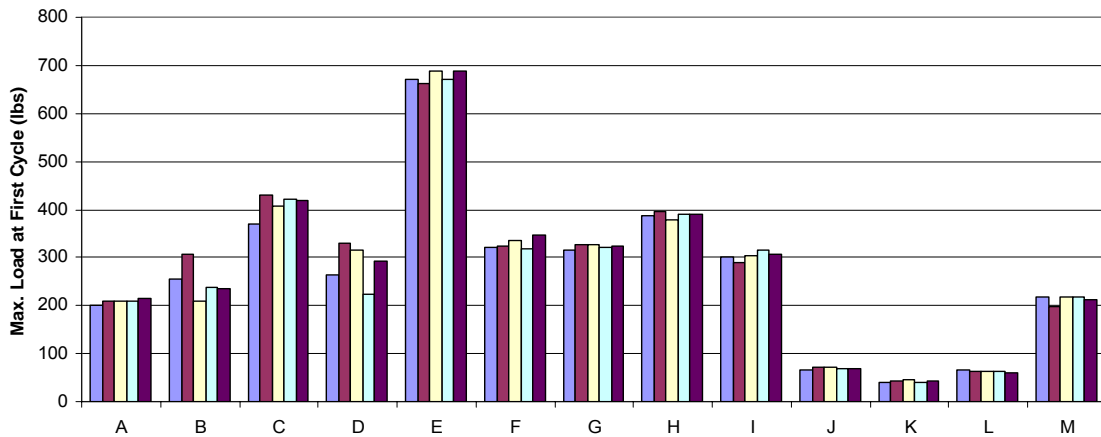


Figure 24. Crack Sealant Test Results: Max. Load at 45 °F.

- The above observations clearly indicate that the crack sealant tester can be used as a screening tool to evaluate the adhesion performance of crack sealants, as clearly shown in Figures 22 and 23. The recommended screening temperatures are 45 °F and 33 °F. Firstly, the crack sealant adhesion test is recommended to run at 45 °F. The poor sealants last less than 400 cycles at 45 °F, which takes around 70 min. to finish the test. If the sealants pass the screening test at 45 °F, the next screening temperature will be 33 °F. Again, the recommended criterion is 400 cycles, and the test takes only 70 min. Additionally, the maximum load at the first cycle measured at 45 °F is recommended as another parameter to avoid potential pull-out problems in the summer time. The temporary criterion proposed is 100 lb. If the sealants have the maximum load at first cycle less than 100 lb, there is a potential pull-out problem in the summertime. These conclusions are tentative and need field evaluation.

SUMMARY

This chapter discussed the test results of all 13 crack sealants. It was found that the adhesion performance of the crack sealants is very sensitive to the temperature so that it is important to select proper sealants for different temperature zones in Texas. Also, the test results indicated that the crack sealant adhesion test can clearly screen out the poor sealants from the good adhesive sealants. The first screening temperature is recommended at 45 °F and the screening cycles are 400. Based on this criterion, the sealants were classified as Groups A and B. Group A sealants had adhesive failure before reaching 400 cycles. Instead, Group B sealants had no adhesive failure to reach 400 cycles. To further evaluate Group B sealants, a second screening temperature of 33 °F was recommended. Additionally, a temporary criterion of maximum load at first cycle measured at 45 °F was proposed to avoid a potential pull-out problem in the summertime in Texas.

CHAPTER 4

DRAFT CRACK SEALANT SPECIAL SPECIFICATION

INTRODUCTION

Current crack sealant classification and specification in Texas is presented in [Table 1](#), which is mainly based on the content of the crumb rubber content and penetration test. Additionally, Class B sealants are required to pass the bond test. It has been recognized that these tests are not well related to adhesive failure that is the most often observed failure in the field. The results presented in [Chapter 3](#) clearly show the capability of the crack sealant tester to differentiate the adhesive performance of the 13 sealants. It is highly recommended to include the crack sealant adhesion test into the specification. This chapter discusses a draft crack sealant specification recommended for TxDOT's consideration.

Table 1. Rubber-Asphalt Crack Sealer (22).

Property	Test Procedure	Class A		Class B	
		Min	Max	Min	Max
CRM content, Grade A or B, % by wt.	Tex-544-C	22	26	-	-
CRM content, Grade B, % by wt.	Tex-544-C	-	-	13	17
Virgin rubber content ¹ , % by wt.		-	-	2	-
Flash point ² , COC, °F	T 48	400	-	400	-
Penetration ³ , 77°F, 150 g, 5 sec.	T 49	30	50	30	50
Penetration ³ , 32°F, 200 g, 60 sec.	T 49	12	-	12	-
Softening point, °F	T 53	-	-	170	-
Bond ⁴	D5329	-		Pass	

1. Provide certification that the min. % virgin rubber was added.
2. Before passing the test flame over the cup, agitate the sealing compound with a 3/8- to 1/2-in. (9.5- to 12.7-mm) wide, square-end metal spatula in a manner so as to bring the material on the bottom of the cup to the surface, i.e., turn the material over. Start at one side of the thermometer, move around to the other, and then return to the starting point using 8 to 10 rapid circular strokes. Accomplish agitation in 3 to 4 sec. Pass the test flame over the cup immediately after stirring is completed.
3. Exception to T 49: Substitute the cone specified in ASTM D 217 for the penetration needle.
4. No crack in the crack sealing materials or break in the bond between the sealer and the mortar blocks over 1/4 in. deep for any specimen after completion of the test.

DRAFT CRACK SEALANT SPECIAL SPECIFICATION

This study mainly focused on the adhesive failure using the crack sealant tester. However, to perform well in the field, other properties of crack sealants, such as viscosity and flash point, must also be considered. Referring to the current specification as presented in [Table 1](#), the parameters included in the special specification are listed below:

- Min. no. of cycles to failure: this parameter controls the potential adhesive failure of the crack sealants.

- Min. peak load: this parameter controls the stiffness of sealants at medium to low temperature;
- Min. softening point: this parameter controls the stiffness of sealants at high temperature. Sealants must be stiff enough not to track in the summer.
- Min. flash point: this parameter is related to safety.
- Min. viscosity: this parameter is useful in making the sealants flow into the crack during construction.

Based on the crack sealant adhesion test results presented in [Chapter 3](#) and the existing specification listed in [Table 1](#), a draft special specification is shown in [Table 2](#). The flash point and softening point are taken from the existing specification. The maximum apparent viscosity of 25,000 cP is added based on the specification for emulsified crack sealant. Two additional parameters from the crack sealant adhesion test are the minimum cycles to failure and the minimum peak load in the first cycle. As shown in [Table 2](#), the sealants are mainly classified based on the minimum cycles to failure at two test temperatures. Currently, 400 cycles to failure is selected as the criterion. The process of classifying a sealant is described as follows:

- Step 1: Run the sealant adhesion test at 45 °F.
 - If the sealant lasts less than 100 cycles, then the sealant is not acceptable; 100 cycles is selected as a minimum requirement to avoid very poor sealants.
 - If the sealant fails between 100 and 400 cycles, then the sealant is classified as Type A;
 - If the sealant does not fail after 400 cycles, then go to Step 2.
- Step 2: Run the sealant adhesion test at 33 °F.
 - If the sealant lasts less than 400 cycles, then the sealant is classified as Type B;
 - Otherwise, it is Type C.

Also, it is worth noting that the current sealant adhesion test requires five replicates of each sealant. The criterion of the 400 cycles to failure is a practical number. It only takes 70 minutes to test one specimen and around one day (6 hours) to finish testing all five replicates.

Based on the draft special specification, the 13 sealants tested previously can be classified as follows:

- Unacceptable: Sealants B, C, D, E, and K
- Type A: Sealant A
- Type B: Sealants F and G
- Type C: Sealants H, I, J, L, and M

Table 2. Performance-Related Crack Sealant Special Specification.

Property	Test Procedure	Type-Grade					
		Type A		Type B		Type C	
		Min	Max	Min	Max	Min	Max
Sealant Adhesion Test:							
Test temperature, °F	Tex 5XX-C	45		45		33	
Cycles to failure		100	400	400	-	400	-
Peak load of first cycle, lb		100	-	100	-	100	-
Flash point, COC, °F	T 48	400	-	400	-	400	
Softening point, °F	T 53	170	-	170	-	170	-
Apparent viscosity, 400°F, cP	D 2196, Method A	-	25,000	-	25,000	-	25,000

NEW SPECIFICATION-BASED SEALANT RECOMMENDATION FOR DIFFERENT DISTRICTS

As clearly shown previously, the sealants adhesion performance is highly dependent upon the test temperature, and this issue is addressed in the draft special specification by classifying sealant type mainly based on the cycles to failure at different temperatures. Therefore, the sealant recommendation for each district will be based on its specific low-temperature (climatic) condition. Figure 25 shows a county-based freeze-thaw cycles map for Texas. It is apparent that the northern panhandle area (such as Amarillo and Lubbock districts) has almost nine times more freeze-thaw cycles than the southern Rio Grande valley area (such as Corpus Christi and Pharr Districts). Different types of sealants should be recommended for these different climates. Based on the test results discussed in Chapter 3, the draft specification proposed in Table 2, and the freeze-thaw cycles shown in Figure 25, a sealant type recommendation is made for each district:

- Type A: Pharr, Laredo, Corpus Christi, San Antonio, Houston, Beaumont, Yoakum, Bryan, and Lufkin
- Type B: Abilene, Atlanta, Austin, Brownwood, Dallas, El Paso, Fort Worth, Odessa, Paris, San Angelo, Tyler, Waco, and Wichita Falls
- Type C: Amarillo, Childress, and Lubbock

Additionally, it should be noted that the cost for each sealant is different. Table 3 lists the price quotes for 11 sealants shipped to San Antonio, Texas, in March 2008. After considering the price quotes shown in Table 3, the final recommended sealants to use in Texas are listed below:

- Type A: Sealant A
- Type B: Sealants F and G
- Type C: Sealants H, L, and M

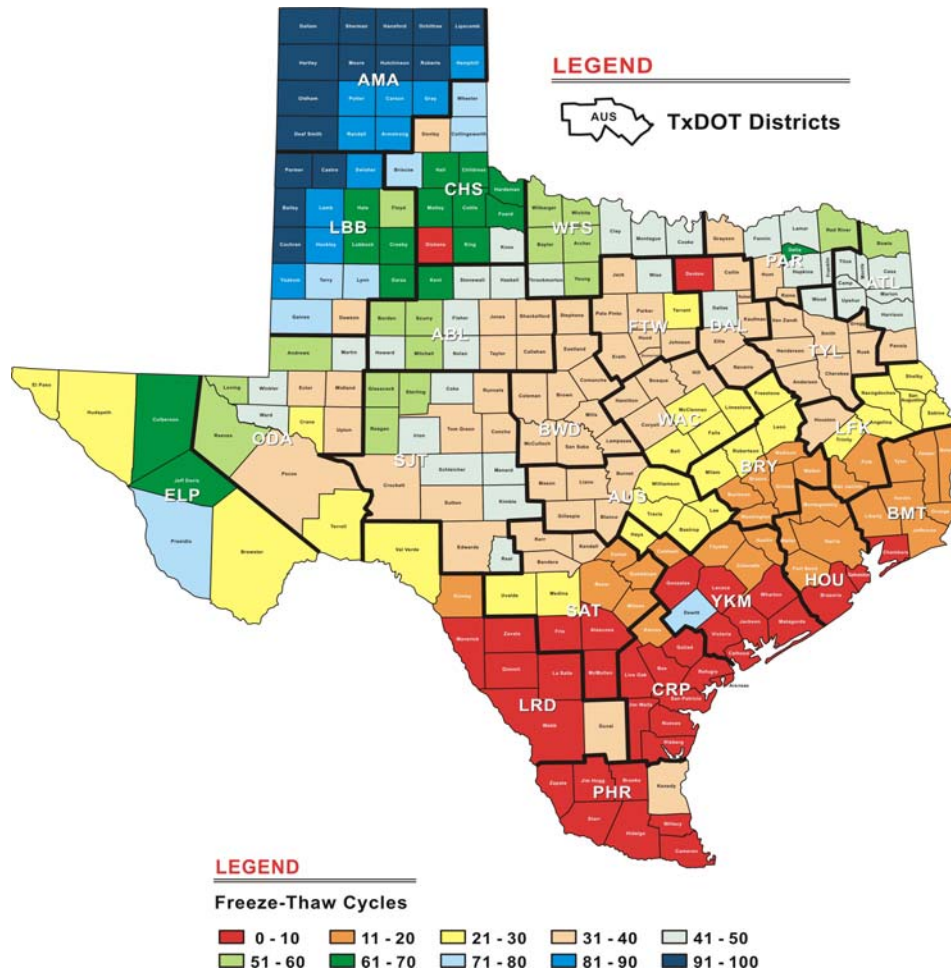


Figure 25. Freeze-Thaw Cycles in Texas.

Table 3. Price Quotes for Different Sealants Evaluated in This Study in March 2008.

Sealants	Truck Load Quantity (lbs)	Price Per lbs (Including Freight Cost)	Price per Truck Load (Including Freight Cost)	Sealant Type*
A	47,840	\$0.250	\$11,960.00	Type A
C	45,000	\$0.291	\$13,095.00	Unacceptable
D	45,000	\$0.377	\$16,965.00	
F	45,000	\$0.311	\$13,995.00	B
G	45,000	\$0.313	\$14,085.00	
H	45,000	\$0.327	\$14,715.00	Type C
I	45,000	\$0.401	\$18,045.00	
J	45,000	\$0.385	\$17,325.00	
K	45,000	\$0.448	\$20,160.00	Unacceptable
L	45,000	\$0.364	\$16,380.00	Type C
M	45,000	\$0.367	\$16,515.00	

Note: Sealants are classified based on the draft special specification shown in Table 2.

PROPOSED FIELD VALIDATION PLAN FOR THE DRAFT SPECIAL SPECIFICATION

The draft crack sealant special specification is recommended based only on the laboratory test results. It is critical to construct field experimental test sections to validate this specification, specifically, the low and high limits in [Table 2](#). It would be ideal to consider the following factors when designing experimental test sections to validate these recommendations:

- Three climatic zones: cold, warm, and hot
- Two traffic levels: light traffic (<3 millions ESALs@20years traffic with the average daily traffic [ADT] around 3500) and heavy traffic (>10 millions ESALs@20years traffic with the ADT around 12,000)
- Four type of sealants: unacceptable, Type A, Type B, and Type C

Note that an unacceptable sealant is included in order to validate the minimum requirement of the cycles to failure for Type A sealant (i.e. 100) proposed in [Table 2](#).

Based on the available information, [Table 4](#) proposes an experimental test plan. A total of seven sealants and 13 test sections are proposed. It is critical to evaluate and document the severity and extent of the existing cracking and to document pavement support conditions. Also, to avoid construction quality issues it would be ideal to have the same crew to complete all of the construction work. Additionally, it is recommended that these test sections be continuously monitored for 3-4 years. In addition to visual observations of adhesion failure rates after the cold weather, pull out failures during the hot summer months should be evaluated as well. It would also be advisable to measure pull off strength in the field. Samples can also be taken and returned to the laboratory for evaluation.

Table 4. Proposed Field Experimental Test Sections.

District	Climatic zone	Sealant	Traffic level	
			Light	Heavy
San Antonio	Hot	Unacceptable: Sealant C	√	
		Type A: Sealant A	√	√
Fort Worth	Warm	Type B: Sealant F	√	√
Lufkin	Warm	Type A: Sealant A		√
		Type B: Sealant G	√	
Amarillo	Cold	Type B: Sealant G	√	√
		Type C: Sealant H		√
		Type C: Sealant L	√	√
Lubbock	Cold	Type C: Sealant M	√	√

SUMMARY

This chapter mainly discussed the draft crack sealant special specification in which three sealant types are proposed: Types A, B, and C. Furthermore, based on the lab test results, climatic condition (freeze-thaw cycles) of each district, and sealant cost, a preliminary recommendation on optimum sealant type for each district has been made. Finally, an experimental test plan was proposed to validate the draft crack sealant special specification.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Based on the research presented in this report, the following conclusions and recommendation are made:

CONCLUSIONS

- The Overlay Tester based crack sealant adhesion tester and associated test protocol were developed. As part of the test protocol, guidelines were developed for specimen preparation, test conditioning, and data interpretation. A detailed test protocol is attached in the [appendix](#).
- A total of 13 sealants have been evaluated using the proposed sealant adhesion test. The proposed test equipment and protocol were found to easily distinguish the poor adhesion sealants from the good ones.
- As part of this study researchers compared TxDOT current crack sealants with several new sealants proposed by sealant vendors. Many of the new sealants were found to have significantly better performance in the new adhesion test.
- The draft crack sealant special specification was proposed. Significantly different from the current crumb rubber content based specification, the new special specification is intended to be performance based; primarily on the performance in the crack sealant adhesion test. Meanwhile, other factors such as flash point, softening point, and viscosity are also considered. In the new special specification, the sealants are classified as:
 - Type A: min. 100 cycles to failure at 45 °F
 - Type B: min. 400 cycles to failure at 45 °F
 - Type C: min. 400 cycles to failure at 33 °F
- Extensive studies were conducted to determine the sensitivity of the test results to test temperature. The sealants were found to be very sensitive to test temperature. Based on these results tentative recommendations were made on sealant type selection for each TxDOT district.
- Finally, an experimental test plan was developed to validate the drafted crack sealant special specification.

RECOMMENDATIONS

Significant progress has been made in laboratory evaluation of the crack sealant adhesion failure and a draft crack sealant special specification has been proposed. The researchers strongly recommend that the findings from this research project will eventually be implemented statewide; in the short term it is proposed that TxDOT construct experimental test sections in four districts to validate and/or refine the draft crack sealant special specification. Also, each district is encouraged to try the new sealants recommended from this study.

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APPENDIX

CRACK SEALANT ADHESION TEST PROTOCOL

Crack Sealant Adhesion Test Protocol

1. SCOPE

- 1.1 Use this test method to determine the susceptibility of crack sealant to adhesive failure. This test subjects the test sample to repeated direct tension cycles. The load on each cycle is measured, and the number of cycles to adhesive failure is defined.
- 1.2 The values given in parentheses (if provided) are not standard and may not be exact mathematical conversions. Use each system of units separately. Combining values from the two systems may result in nonconformance with the standard.

2. APPARATUS

- 2.1 *Crack Sealant Tester* - The device is an electro-hydraulic system that applies repeated direct tension loads to specimens. The test setup is shown in [Figure 1](#). It has an air chamber that controls the test temperature from 23 °F (-5 °C) to 104 °F (40 °C). The machine features two hard-anodized aluminum blocks with the sealant under test between them. One block is fixed and the other cycles horizontally. The device automatically measures and records load, displacement, and temperature every 0.1 sec. The data collection is automated.

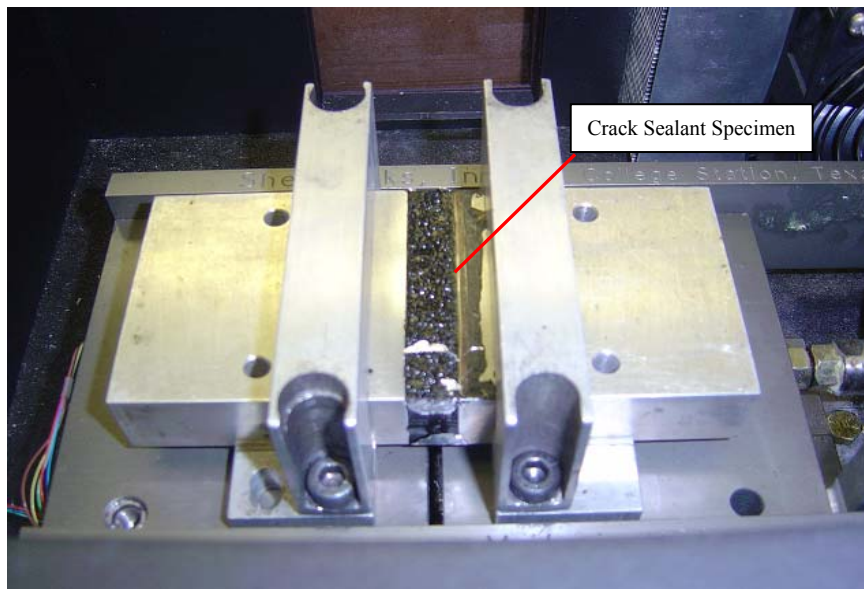


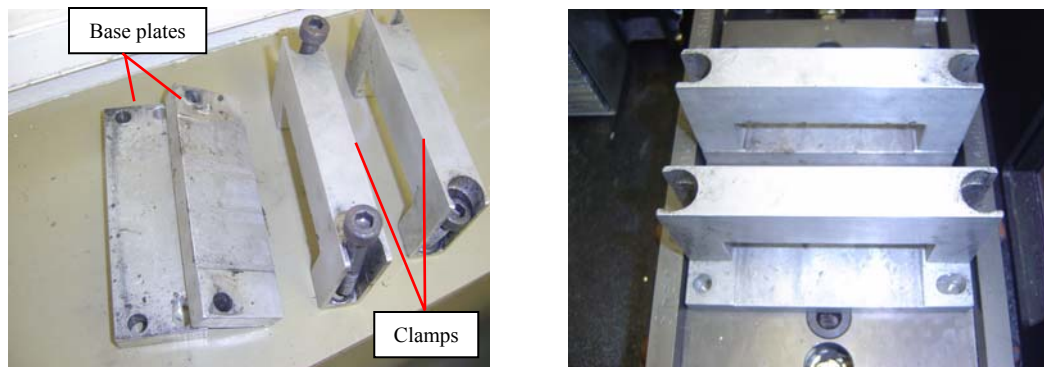
Figure 1. Specimen Setup in the Air Chamber of Crack Sealant Tester.

Note 1 – the crack sealant tester shall meet the following specification regarding load, displacement, and temperature chamber:

- 1) Electronic displacement measuring system with a range of at least ± 0.1 in. with a throughput resolution of 0.0001 in. or better;
- 2) Electronic load measuring system with a full-scale range of ± 5 kip and accuracy of 0.25% of full scale or better.
- 3) Temperature chamber capable of controlling the test temperature in the test space over the range from 23 to 104 °F within a tolerance of ± 1 °F, when room temperature is between 65 and 80 °F. Additionally, a temperature sensor shall be mounted in the chamber to control the temperature, and provide continuous temperature readings during the test.

The test is a fixed displacement test with a maximum displacement of 0.1 in. (0.25 cm). The displacements are applied in a triangular waveform. One cycle takes 10 seconds, 5 seconds opening and 5 seconds closing.

Additionally, the test equipment also includes two clamps which are used to secure the test blocks to the tester, see [Figure 2](#).



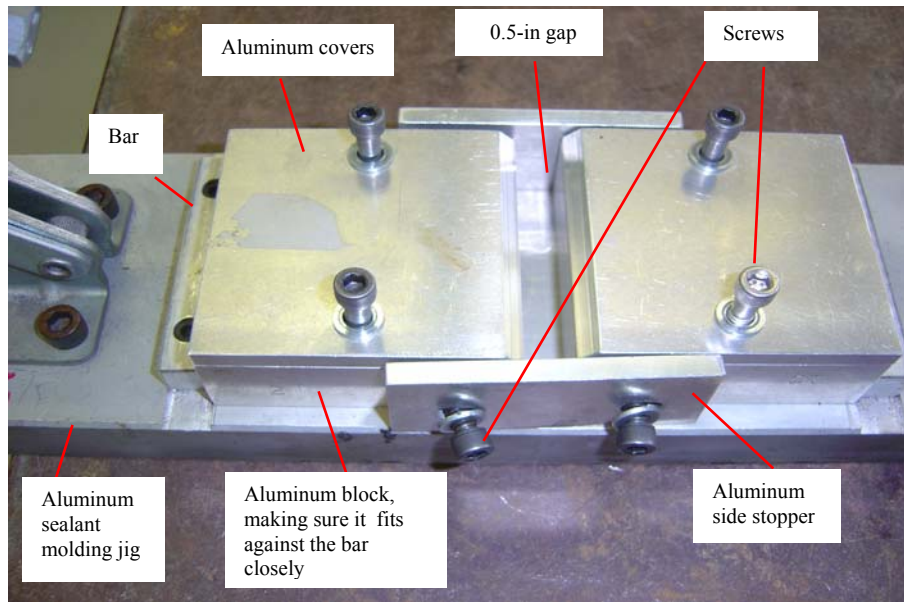
a) Clamps and base plates

b) Clamp assembly

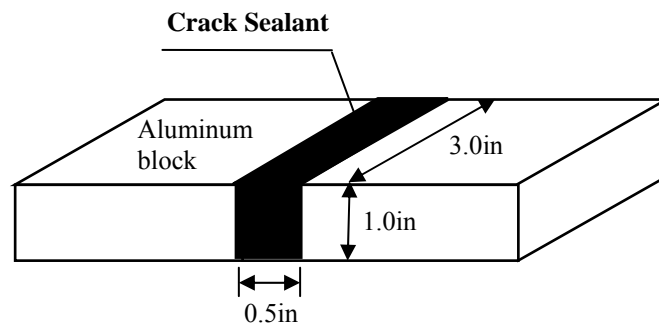
Figure 2. Clamps and Their Assembly in Crack Sealant Tester.

- 2.2 *Oven* – The maximum heating temperature is not less than 400 °F. The heat source shall be thermostatically controlled and capable of maintaining the target temperature within a tolerance of ± 10 °F.
- 2.3 *Environmental chamber* – a chamber maintained at a fixed temperature of 41 ± 2 °F is recommended for preconditioning the sealant specimens.
- 2.4 *Mold* – Specially designed sample preparation molds are supplied with each device. [Figure 3a](#) shows the mold and [Figure 3b](#) illustrates the dimensions of the crack sealant sample. The preparation of the test samples will be described later.

Note 2 – It is very important to ensure that the test surface of the aluminum blocks are not touched or scratched as this will influence the test result. Cleaning and preparation procedures are described below



(a) Sealant mold.



(b) Dimensions of crack sealant sample.

Figure 3. Sealant Mold and Dimensions of Crack Sealant Sample.

2.5 *Allen wrench.*

2.6 *“T” handle Allen wrench.*

2.7 *1/2-in drill with core barrel, as shown in [Figure 4](#).*

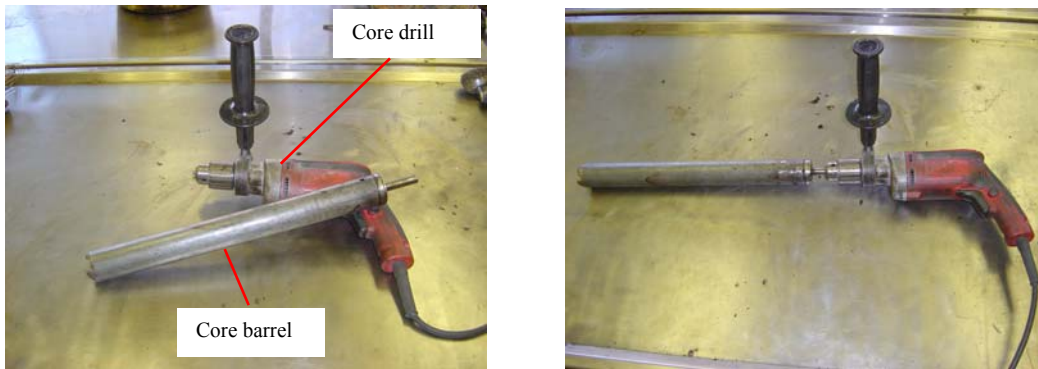


Figure 4. Drill and the Core Barrel for Drilling Sample Sealant.

3. MATERIALS

- 3.1 12-in. wide aluminum foil
- 3.2 1/4-in. wide adhesive tape
- 3.3 6×9-in. (152×228 mm) scotch hand pads
- 3.4 Wiping cloths
- 3.5 Acetone
- 3.6 Mapp gas
- 3.7 6 in. long screwdriver
- 3.8 3-in. stiff putty knife scraper
- 3.9 Petroleum jelly
- 3.10 Washable glove
- 3.11 Ovenproof glove
- 3.12 12 in. diameter bowl
- 3.13 Spoon
- 3.14 Stopwatch

4. SEALANT SPECIMEN PREPARATION

Sampling Sealants from Box

- 4.1** *Preparing the Core Drill* — Clean the inner and outer surface of the core barrel, and then lubricate both surfaces using petroleum jelly. Finally, mount the core barrel to a drill, as shown in [Figure 4](#).
- 4.2** *Sampling Sealant* — Drill the sealant from the suppliers box. Refer to [Figure 5 a\)](#). Extrude the sealant from the core barrel using the screwdriver, and then lay it on the aluminum foil. See [Figures 5 b\)](#) and [5 c\)](#).

Approximate 1.5 lbs of sealant is needed to prepare 5 specimens as described later.

- 4.3** *Trimming the Sealant Sample* — Trim the sampled sealant ends (remove 1/8 in.) using a hot putty knife, refer to [Figure 5 d\)](#).

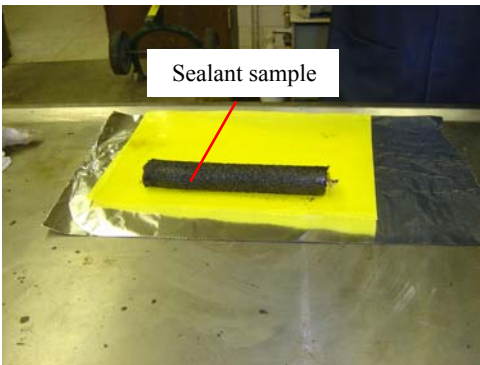
Store the trimmed sealant in a 12 inches diameter aluminum bowl.



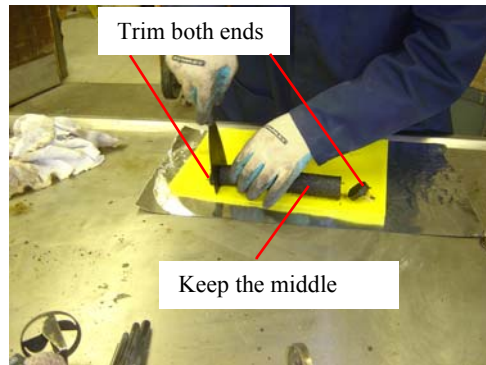
a) Drill box sample of sealant



b) Extrude the sample



c) Lay sample on a plastic bag



d) Trim ends keeping the middle part

Figure 5. Drill and Trim the Sealant Sample.

Assembling Mold

- 4.4** *Cleaning Aluminum Blocks* — Clean the testing surface of each aluminum block using acetone or other solvents.

Brush the test surface of each aluminum block uniformly using a scotch hand pad, as shown in [Figure 6](#). Then re-clean the testing surface of each aluminum block with acetone.



Figure 6. Clean Testing Surface.

- 4.5** *Preparing Aluminum Foils* — Prepare 15 pieces of rectangle aluminum foil with two different sizes: 5 pieces of Foil A with 2.0×12.0 inches (see [Figure 7a](#)) and 10 pieces of Foil B with 3 × 4 inches (see [Figure 7 b](#)).
- 4.6** *Assembling Mold* — Put a Foil A in the center of the sealant molding jig, and then put two aluminum blocks over the Foil A. Refer to [Figure 7 a](#)).

Note 3 — the aluminum blocks are paired and a pair of block is marked with the same number.

Wrap up the inclined part of the aluminum cover using the Foil B, and then put it over the aluminum block. Refer to [Figure 7 b](#)).

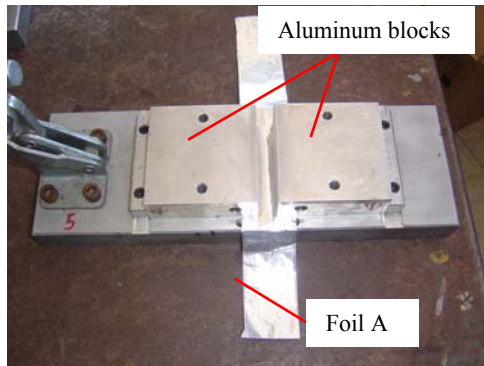
Assemble both aluminum blocks and aluminum covers into the sealant molding jig using screws. Tape the Foil B using adhesive tape to the aluminum covers. Refer to [Figure 7 c](#)).

Mount the side stoppers on both sides of the aluminum blocks, and then tighten them with screws. Refer to [Figure 7 d](#)).

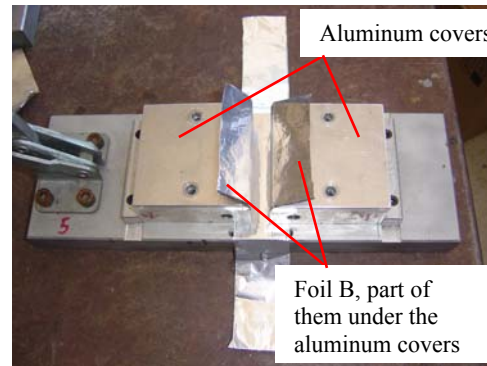
Note 4 — during the assembly, the aluminum blocks should completely contact the bars fixed on the molding jig in order to get exactly a half inch gap between two blocks. It is worth noting that the gap width has a significant influence on the

test result. Additionally, the testing surface of aluminum blocks should not be touched during the whole assemble process; otherwise, test results may vary a lot between specimens.

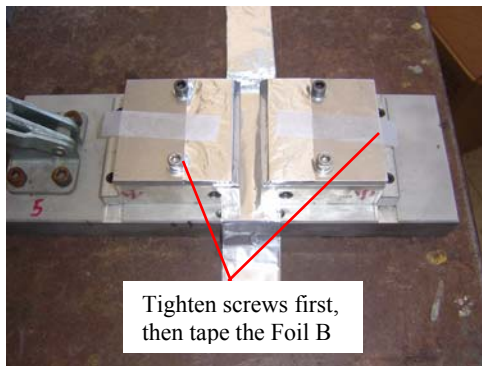
Note 5 — for each sealant at every test temperature, five sets of molds are required. Refer to [Figure 7 e](#)).



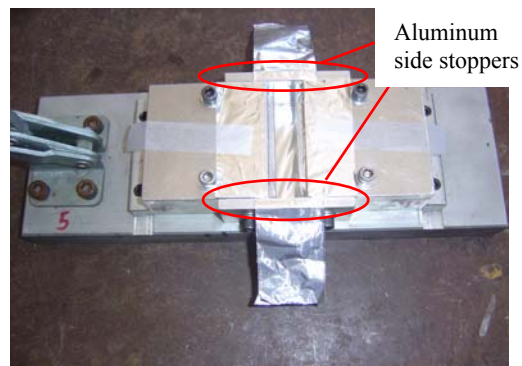
a) Put the Foil A and aluminum blocks



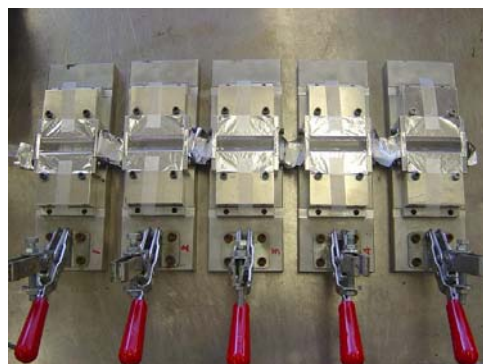
b) Put the Foil B and aluminum covers



c) Tighten screws and tape the Foil B



d) Mount aluminum side stoppers



e) Five assembled sealant molds

Figure 7. Mount the Mold.

Molding Sealant Specimens

- 4.7** *Heating the Sampled Sealant* — Turn on the oven and set the temperature to the sealant melting temperature recommended by the manufacturers. Put the sampled sealant within a bowl and one spoon into the oven. Wait 2 hours before starting to mold. Meanwhile, set the conditioning chamber temperature to 41 °F (5 °C).

Note 6 — Use the spoon to stir the melted sealant at least 20 cycles in the oven after 60 min. and 80 min., respectively.

- 4.8** *Molding Sealant Specimen* — after a 2 hour heating time, stir and pour the melted sealant into the sealant mold as quickly as possible, meanwhile, shake the sealant molding jig 20 times by hand as quickly as possible. Refer to [Figure 8](#).

Note 7 — Finish the sealant pouring process quickly because the sealant temperature drops very fast. Also, shake the sealant molding jig as quickly as possible to let the air out of the mold.

Note 8 — after pouring and shaking; let the sealant cool down (around 3 min.) before moving the molding jig.

Just after pouring the melted sealant into the mold, put the sealant back to the oven without any delay. Wait 5 min. and then start to mold another sealant specimen. Repeat this process until 5 sealant specimens are molded.

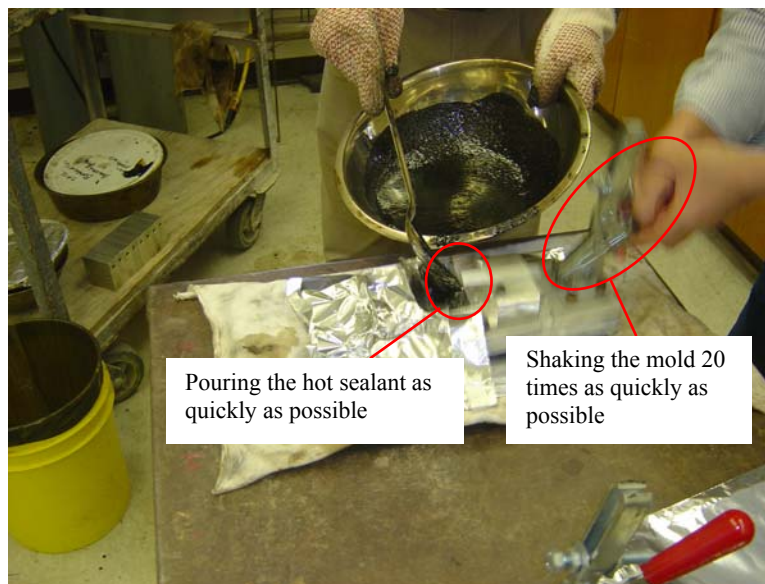


Figure 8. Mold Sealant Specimen.

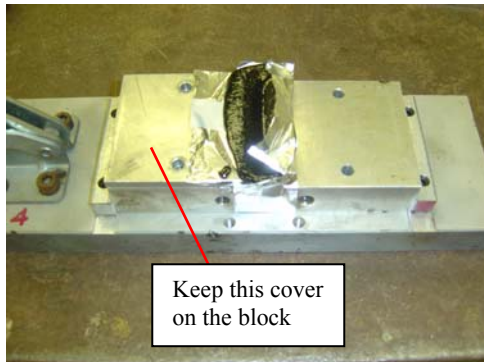
4.9 *Trimming Sealant Specimen* — 40 min. after molding, remove the aluminum side stopper, adhesive tape, and one of the aluminum covers. Refer to [Figure 9 a\)](#).

Note 9 — sealant temperature is close to the room temperature after 40 min. setting time.

Note 10 — leave one of the aluminum covers which is being used as a support for the following trimming. Refer to [Figure 9 a\)](#).

Trim the sealant specimen using the hot putty knife scraper. Refer to [Figure 9 b\)](#), [c\)](#), and [d\)](#).

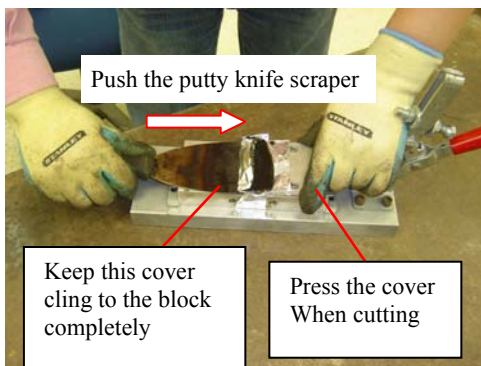
Note 11 — the putty knife scraper should cling totally to the aluminum block and always keep it horizontal when trimming the sealant. After trimming, cover the sealant surface with aluminum foil.



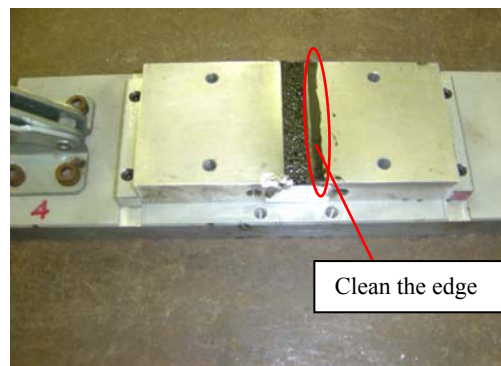
a) Remove screws, side stopper, and one of covers



b) Heat the putty knife scraper



c) Trim the sealant specimen



d) Clean the edge using the putty knife scraper

Figure 9. Trim Sealant Specimen.

- 4.10** *Storing Sealant Specimens* — after trimming 5 sealant specimens, place all of sealant specimens in the environmental chamber of 41 °F (5 °C) and keep them there at least 2 hours before moving them into the crack sealant tester.

Note 12 — about 1 hour after the sealant specimens are placed in the environmental chamber, peel off all the aluminum foil quickly from the sealant surface, and then wrap up every sealant specimen using new aluminum foil. The purpose of doing that is to make removal of the aluminum foil easy when clamping the sealant specimens in the crack sealant tester.

5. PROCEDURE

- 5.1** *Sample Preparation* — prepare 5 sealant specimens according to [Section 4](#).

- 5.2** *Starting Testing Device* — turn on the crack sealant tester, link the machine with the computer, open the software “overlay.exe,” and set up the test temperature.

Take all of the sealant specimens out of the environmental chamber, and then load them into the air bath chamber of the crack sealant tester immediately. Keep the sealant specimens at the specified testing temperature in the machine overnight (or at least 8 hours).

Set the other test parameters in the screen of the “overlay.exe” program, including “Max opening displacement”; “load drop”, “Loading/Unloading Time”, “Number of cycles”, and fill in the information of the test sample, such as “Project Name”, “Specimen ID/Lab”, “Technician’s Name”, “Data File Name”, “Test Remarks” and so on. See [Figure 10](#).

Note 13 — before clamping the sealant specimen, the machine must show “Pump On” status under the “Displacement” control mode.

- 5.3** *Clamping the Sealant Specimen to the Crack Sealant Tester* — after overnight (or 8 hours) conditioning, remove the aluminum foil from the surface of the sealant specimen, and then clamp the sealant specimen down to the crack sealant tester using both the “T” handle Allen wrench and the socket drive handle with the extension. Refer to [Figure 11](#).

Note 14 — Complete this process as quickly as possible in order to limit the temperature change of the sealant specimen.

Note 15 — always keep the trimmed side of the sealant specimen upward, and center the sealant specimen between the two clamps.

- 5.4** *Testing Sealant Specimen* — 1 hour after clamping the sealant specimen, press the “Start” button in the “overlay.exe” program to begin the test.

Note 16 – the test will stop automatically when the data recorded in the software reaches the percentage of load drop or the maximum running cycles.

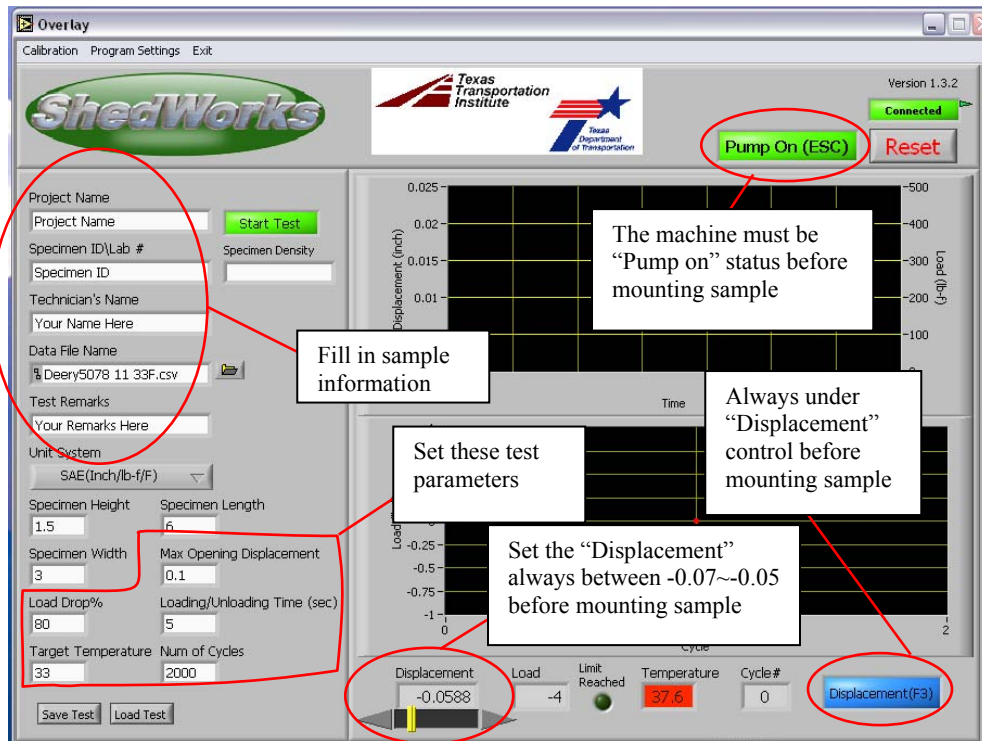


Figure 10. Fill in Test Parameters and Specimen Information.

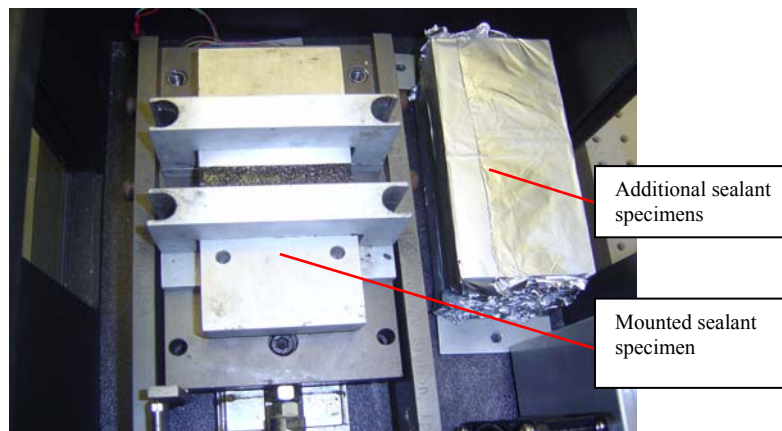
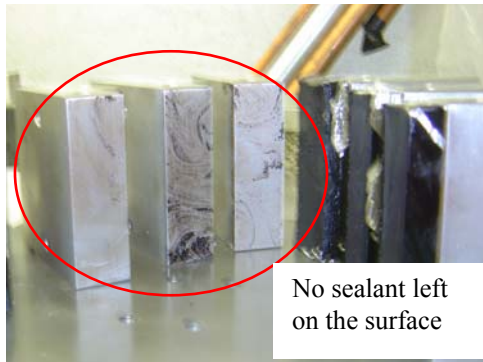


Figure 11. Mount Sealant Specimen in the Crack Sealant Tester.

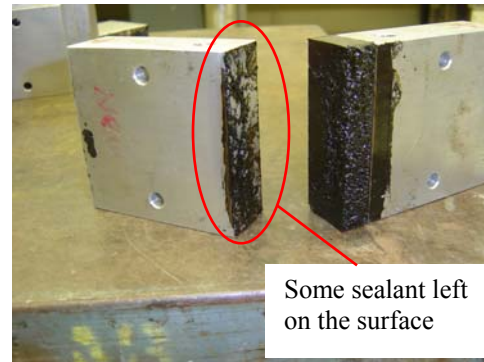
6. REPORT

Report the following for each specimen:

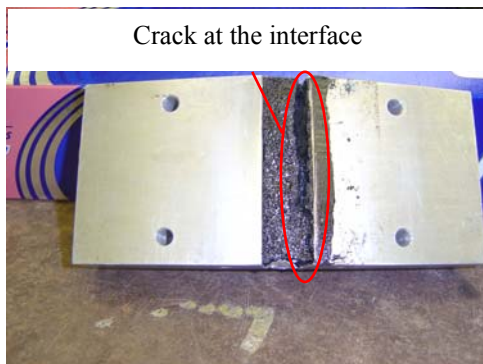
- test temperature;
- percentage of load drop;
- maximum load of first cycle;
- number of cycles to the defined load drop (adhesive failure assumed after 80 percent drop in load from the load measured on the first cycle); and
- adhesive failure type. (Refer to [Figure 12](#)).



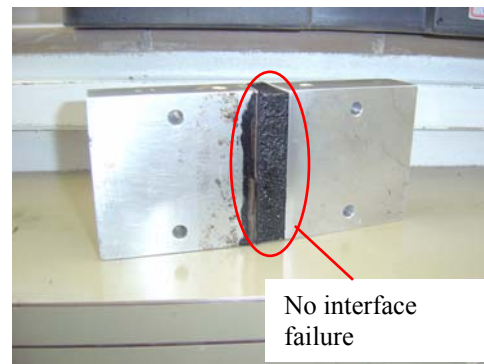
a) Typical adhesive failure



b) Partial adhesive failure



c) Minor adhesive failure



d) No adhesive failure

Figure 12. Failure Types Observed.