

**Effectiveness and
Performance of Crack
Sealants for Bridge
Decks**

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**EFFECTIVENESS AND PERFORMANCE
OF CRACK SEALANTS FOR BRIDGE DECKS**

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16. Abstract The primary objective of this study was to assess the effectiveness and performance of selected products for sealing cracks in concrete bridge decks. The project was a follow up study of an earlier investigation to expand the selection of crack sealers for use in the field. A total of nine crack sealants were tested in this study under laboratory conditions that simulated the exposure to deicing salts and freeze-thaw cycles encountered in practice. Five of the products had been tested earlier under the same laboratory conditions but for a limited range of crack widths. Four additional products were also included in this study. Based on the test results, the performance of the sealants was evaluated and ranked, and recommendations for their use in the field are provided.		

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Executive Summary

In a previous investigation conducted for WisDOT, recommendations for the use ten, commercially available crack sealers were provided for a variety of crack widths. As the viscosity of the products can vary widely, sealants are often specified only for narrow range of crack widths. Accordingly, the previous study assessed the sealants only within the crack width range specified by the manufacturer. In practice, however, bridge decks may present a wide range of crack widths (often outside of the range specified by a given manufacturer), and as a result different types of sealants would need to be specified for a given deck. This is often impractical and ideally, it would be desirable to specify a single type sealant over the entire deck.

The primary objective of this study was to conduct additional laboratory tests on the best performing sealants by including crack widths outside of the manufacturer's specified range of crack widths. A secondary objective was to identify and test new products that might have appeared in the market since the previous study. To meet this objective, a total of nine ten crack sealants were selected for study under laboratory conditions that simulated the exposure to deicing salts and freeze-thaw cycles encountered in practice. Five of the products had been tested earlier under the same laboratory conditions but for a limited range of crack widths. Four additional products were also included in this study.

The investigation was divided into two components. In the first component, sealant performance was assessed by measuring its ability to penetrate and fill cracks of prescribed widths. Four crack widths, representative of those encountered in practice, were considered: hairline, narrow, medium and wide cracks. In the second component of the study, the bond strength and durability of the sealants was assessed. The bond strength of the crack sealants was measured in

specimens with and without exposure to freeze-thaw cycles in order to evaluate the possible deterioration of the sealants under extreme environmental conditions.

Based on the test results, crack sealants were assigned to a performance group category depending on their measured performance. The performance of crack sealants depended in part on the crack width considered; however, all of the sealants showed excellent or very good performance within the crack width range specified by the manufacturer. Sikadur 55 SLV was found to be the best performing sealant overall, followed by TK-9030-N, Degadeck, Denedeck which also showed very performance. All of these products are recommended for use for hairline, narrow, medium and wide cracks. The remaining products tested in this study are recommended for use only within the crack width specified by the manufacturer.

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CHAPTER 1

Introduction

1.1 Background

Deicing salts, which are generally mixtures of sodium chloride and calcium chloride, are commonly broadcast over bridge decks during Wisconsin winters. As ice melts, it mixes with the deicing salt to form a salt water solution, which remains ponded on the surface of the bridge deck. Although the use of epoxy coated bars has served to deter corrosion of reinforcing bars in bridge decks built in the last 25 to 30 years, chlorides may penetrate through the deck and induce corrosion of the steel substructure, or of the reinforcing steel bars in the case of a concrete substructure.

To prevent or reduce chloride ion intrusion, decks can be protected by sealing the surface of the deck. Currently available deck sealers are primarily silanes and siloxanes (derivatives of silicone), and are intended to be applied during the final stages of construction to protect the deck against chloride ion intrusion.

Many concrete bridge decks in the United States have developed cracks shortly after construction (Krauss and Rogalla, 1996). These cracks sometimes extend through the full depth of the deck and are usually spaced three to 10 feet apart along the length of the bridge. Consequently, chlorides can penetrate into the deck through the cracks, even if the deck was properly sealed at the time of construction. Crack sealants are often used to penetrate, fill, and bond existing cracks back together, and to deter chloride ion intrusion. These sealants are expected to bridge and seal fine cracks in a deck by creating a barrier that prevents water and water-borne contaminants from entering the concrete. Also, they must be able to endure crack opening and closing due to thermal effects and deck movements. Currently available crack sealant products include High Molecular Weight Methacrylates (HMWM) resins, epoxy resins, and urethane resins among others.

In a previous study (Pincheira and Dorhorst, 2005) ten, commercially available, crack sealants for use in bridge decks were evaluated. The sealants studied were chosen based on

feedback from WisDOT District Bridge Maintenance Engineers and manufacturer product data in consultation with the Project Oversight Committee. The performance of the sealants was assessed by measuring its ability to penetrate and fill cracks of prescribed widths, and by measuring its bond strength with and without exposure to freeze-thaw cycles. Based on the results of the study, crack sealants were assigned to a performance group category depending on their measured performance. Sealants that offered the best performance were assigned to Performance Group Category I, those that showed moderate reductions in performance under freeze-thaw conditions were assigned to Performance Group Category II, and those that showed significant reductions in performance under freeze-thaw cycles were assigned to Performance Group Category III. The performance of the sealants depended in part on the crack width considered. Table 1.1 shows a summary of the obtained sealant performance according to the crack width considered.

Table 1.1 Summary of crack sealant performance (Pincheira and Dorshorst, 2005)

Hairline (< 0.06 in.)	Narrow ($0.06 - 0.10$ in.)	Medium ($0.10 - 0.19$ in.)	Wide (> 0.20 in.)	Performance Category
Sikadur 55 SLV	Sikadur 55 SLV	Sikadur 55 SLV	No products tested	I
Dural 335				
Sikadur 52	Sikadur 52	Sikadur 52	No products tested	II
Degadeck	Degadeck	Degadeck		
Denedeck	Denedeck	Denedeck		
SikaPronto 19	SikaPronto 19	SikaPronto 19	Duraguard 401	III
Duraguard 401	Duraguard 401	Duraguard 401	TK 9000	
	TK 9000	TK 9000		
	TK 9030	TK 9010		

In that study, crack sealants were tested only for the crack widths specified by the manufacturer. Most sealants were specified to be applied for small, medium or large crack widths, and not over the entire crack width range that may be encountered in practice, i.e., hairline to wide cracks. As shown in Table 1.1, only two products were recommended for use (Category I – best performance) for hairline crack widths, one product in the narrow and medium crack widths, and no products for wide crack widths. In category II, there are three

products for hairline, narrow, and medium crack widths, but again no products for wide cracks. In practice, however, bridge decks may present a wide range of crack widths, which means that different products would have to be specified if the best performing sealers are to be used. For this reason, WisDOT was interested in testing the best performing sealants over a wider crack width range so that a single product may be specified for the entire range of crack widths.

1.2 Objective

The main purpose of this study was to conduct additional tests in order to provide a wider selection of crack sealers for use in the field. Specifically, this objective was met by:

- a) conducting additional tests on the sealants in Category I and II for crack widths other than those specified by the manufacturer.
- b) identifying and testing new products that might have become available in the market since the previous study was conducted.

1.3 Scope

Following the recommendations of the Project Oversight Committee, a Grade D concrete mix design as designated in the Wisconsin Bridge Manual was used for all concrete specimens, as was done in the previous study. The performance of the crack sealants was evaluated for four crack widths as defined in the current WisDOT Bridge Inspection Pocket Manual. The effect of freeze-thaw cycles on the performance of the crack sealants was also evaluated according to ASTM C 666.

CHAPTER 2

Background and Sealants Selected for Study

2.1 Introduction

In this chapter, the main characteristics of crack sealants are briefly discussed. Also, the methods used for evaluating the crack sealers are briefly summarized. A more exhaustive description and review of the literature has been presented elsewhere (Pincheira and Dorshorst, 2005).

2.2 Main Characteristics and Application Procedures

Several criteria must be considered when selecting a crack sealant for use on a bridge deck. Characteristics such as depth of penetration and weather resistance provide information on the expected performance of a product, while others offer information related to field preparation and application procedures.

Currently available crack sealant products include High Molecular Weight Methacrylates (HMWM) resins, epoxy resins, and urethane resins among others. Crack sealant products must be able to bridge and seal fine cracks in a deck by creating a barrier that prevents water and water-borne contaminants from entering the concrete.

The amount and surface preparation required before a product is applied to seal a crack is an important consideration when selecting a sealant. Surface preparation requirements for crack sealants range from no specific requirements, to pressure washing or mechanical abrasion to clean the deck surface and remove debris from cracks. Some districts in Wisconsin, for example, use a grinder to enlarge the surface at the top of the crack and then compressed air to clean the crack, thus allowing for better entrainment of the sealer. In addition, the necessary moisture content of the substrate at the time of application can be included in the surface preparation category and can range from completely dry to slightly damp.

The temperature of the deck during and immediately after application of crack sealants as well as expected precipitation conditions after application are both important factors. While products with broader ranges of temperature and environmental conditions during and after application of the product are more attractive, it is generally recognized that cracks should be sealed in the spring or in the fall, preferably early in the morning, when temperatures are low and crack widths are widest.

The application method is a key aspect to consider when evaluating crack sealants because it directly affects the time and equipment required to seal cracks. While gravity feeding sealant into cracks is suitable for many products on the market, some products are designated as pressure injection only. Pressure injecting cracks requires special equipment and will often be more time consuming than gravity feeding cracks. While pressure injection may be a viable option for some Wisconsin Department of Transportation (WiDOT) districts, the equipment used to pressure inject cracks is not readily available to all. In addition, the cost to rent or purchase the necessary equipment, or hire a contractor to pressure inject cracks, combined with the extra time the deck would need to be closed to traffic could make a product with relatively inexpensive material costs become extremely expensive.

Freeze-thaw resistance is crucial to effective performance of sealant products applied to crack of bridge decks in Wisconsin. Since there is not a standard test performed on all the sealants by the manufacturers to measure freeze-thaw resistance, the likelihood of a sealant performing well under freeze-thaw conditions must be established based on product manufacturers' recommendations. Clearly, sealants which are not recommended for use in freeze-thaw conditions should not be considered for used on Wisconsin bridge decks.

2.3 Selection of Crack Sealants

Following the main objective of this study, all products in performance category I and II were tested for the crack widths not considered in the previous study. These sealants are as follows: Sikadur 55 SLV, Dural 335, Sikadur 52, Degadeck and Denedeck. The main characteristics of these products are described elsewhere (Pincheira and Dorhorst, 2005).

Four additional products were also included in this study. One sealer was a modified product from the TK-9030 sealer tested in the previous study (Pincheira and Dorhorst, 2005).

According to the manufacturer, this product was modified to better meet the acceptance criteria and wanted to have it tested for the full range of crack widths. Since its commercial brand name, however, was not modified by the manufacturer, though it was a different product than that tested in 2005, the product will refer to as TK-9030-N hereafter.

The remaining three additional products studied are all produced by the same manufacturer, namely, UNITEX®. These are: Pro-Poxy 50, Pro-Poxy 100 and Pro-Poxy 204. These products belong to the epoxy family and are named with numbers that relate to the level of viscosity. The lower the number, the lower the viscosity of the sealer. Thus, Pro-Poxy 50 is a super low viscosity resin that is appropriate for hairline cracks. Pro-Poxy 100 has a low viscosity and it is more appropriate for narrow to medium crack widths, while Pro-Poxy 204 is a medium viscosity resin suitable for wide cracks.

CHAPTER 3

Test Program

3.1 Introduction

In this chapter, the test program used to assess the performance of the crack sealants is described. Test methods and procedures used are presented. The specimens and testing equipment used are also described.

3.2 Test Program Description

Table 3.1 shows test protocol in each crack width category for the sealants used in this study. As mentioned earlier, Dural 335 and Sikadur 55 SLV were found to be the best performance sealants (Category I) in the previous study, but they were not tested for all crack widths. Degadeck, Denedeck and Sikadur 52 were all in category II, but again, they were not tested for wide crack widths.

According to the manufacturer, TK-9030-N was suitable for all crack widths, and thus it was tested for the entire crack width range. On the other hand, the Pro-Poxy type sealants, were suitable specific crack widths and therefore were only tested in their own crack width category, as shown in the table.

The primary objective of this study was to assess the effectiveness of the selected crack sealants to both penetrate cracks and to bond to crack walls and endure crack opening and closing. To achieve this goal, concrete specimens with a desired crack width were prepared. The crack was then filled with a sealant which was allowed to cure before being tested. The specimen was saw-cut through the thickness and the visible depth of penetration of the sealant was observed and measured. A test procedure similar to ASTM C 496 "Splitting Tensile Strength of Cylindrical Concrete Specimens" was developed to test the bond strength of the sealants. To measure the durability of the bond, additional specimens were prepared and subjected to 300 freeze-thaw cycles before undergoing the bond strength test. Casting,

preparation, and sealing of the concrete specimens, as well as the equipment and test procedures used are described in further detail in the following sections.

Table 3.1 Test protocol

Sealant	Crack Width			
	Hairline ($< 0.06''$)	Narrow ($0.06''$ to $0.1''$)	Medium ($0.1''$ to $0.19''$)	Wide ($> 0.2''$)
Dural 335		X	X	X
Sikadur 55 SLV				X
Sikadur 52				X
Denedeck				X
Degadeck				X
TK -9030-N	X	X	X	X
Pro-Poxy 50		X		
Pro-Poxy 100		X	X	
Pro-Poxy 204				X
X	crack widths to be tested in this study			
	crack widths tested in previous study.			
	Not tested.			

3.3 Description of Test Specimens

A single size concrete specimen was used to conduct bond strength tests. The chosen specimen size was 3 in. by 4 in. by 8 in., which was obtained by casting 3 in. by 4 in. by 16 in. specimens and saw-cutting them in half. This size was chosen because of the desire to create a natural crack through the thickness and the bond strength could be accurately measured with the test equipment in the WSMTL. Also, steel forms were available in the WSMTL for casting the specimens, and the standard freeze thaw cycle test could be adapted to a specimen of that size.

3.3.1 Mix design, Casting and Curing Procedures

A total of three batches were required to prepare all the specimens. The concrete mix design used in the crack sealant test program was the same as that used in the previous study (Pincheira and Dorshorst, 2005). Concrete batches were cast in accordance with ASTM C 192 using the available equipment in the laboratory. Prior to mixing each test batch, a “butter” batch was prepared and mixed. This “butter” batch was used to coat the mixer and to test the fresh air content, which allowed adjustment of the air entrainment if necessary. All batches with acceptable air content and slump, were cast into the molds for each batch. Specimens were given a smooth finish and covered with wet burlap and a polyethylene sheet for 24 hours. Then, the specimens were removed from the forms, labeled and moved to the wet cure room where they remained until 14 days old. The specimens were then removed from the wet cure room and allowed to air cure for an additional 14 days or until the tests were conducted.

3.3.2 Cracking of specimens

While saw cutting cracks into specimens would allow crack widths to be measured very easily and accurately, the cracks would have an unrealistic smooth surface. Thus, each specimen was cracked prior in order to simulate the surface of a real crack. To create the crack, a 5/8 in. wide by 1/4 in. deep notch was saw cut using a masonry saw in the center of each of the two 4 in. by 8 in. faces of the specimens. The notch on the top face of each block was then widened at the ends to 1 1/2 in. to allow for accurate measurement of the crack width. A 9/16 in. diameter steel rod was placed in each notch which concentrated a load through the center of the specimen as shown in Figure 3.3.1.

3.3.3 Formation and Measurement of Crack Widths

At age 28 days, the cracked specimens were removed from the curing area and prepared for sealing. To create a crack with the desired width, folded aluminum foil was placed between the two cracked halves at the ends of the specimen. The four different crack widths were created using varying layers of foil, which were held in place at both ends of the specimen using C-clamps, as shown in Figure 3.3.2. The crack width was measured near the ends of

specimen, using a measuring magnifier resting directly on the surface of the crack. Adjustments were made in either the amount of foil used or the clamping pressure until the target crack width was achieved.

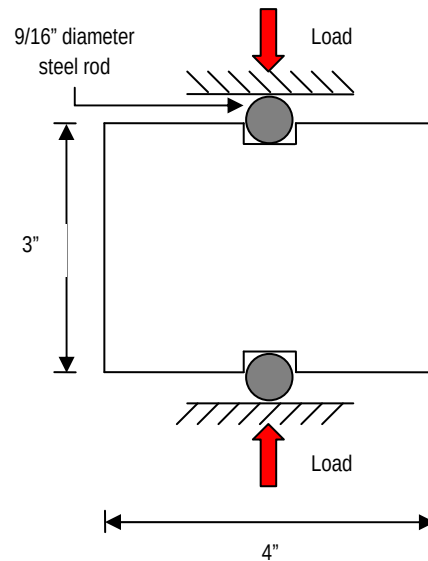


Figure 3.3.1 Setup and dimensions for procedure used to crack specimens

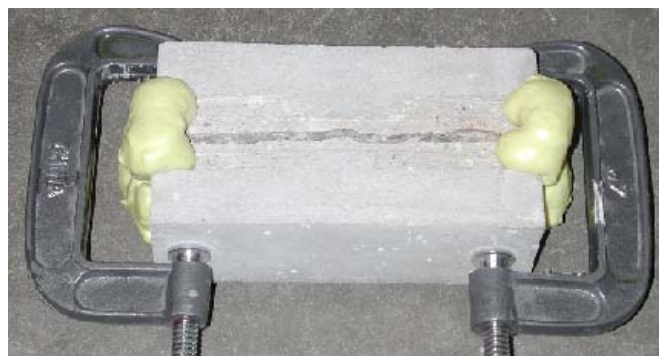


Figure 3.3.2 Typical crack sealer specimen ready to be sealed.

3.3.4 Sealant application

Prior to sealing the cracks with a given sealant, the ends of the specimens were sealed with expansion foam and silicone caulk dried to manufacturers' recommendations (see Fig. 3.3.2). The crack sealants were then mixed according to the manufacturer's specifications using the data sheets from the products. After the products were thoroughly mixed, they were poured over and gravity fed into the crack. Working time for the sealants ranged from five to 30 minutes, during which time enough product was applied to completely fill the crack and pool on the top surface of the crack. Once the cracks were filled, the sealants were allowed to set and dry per the manufacturer's recommendations. Often, however, the sealants were allowed to dry overnight before the clamps were removed, and were given 14 days to cure until testing. Following the two week curing period, half of the sealed specimens were put in the freeze-thaw chambers, while the other half were prepared for the depth of penetration and bond strength tests. Two inches were saw-cut off the ends of each specimen, which was used for the depth of penetration test. The remaining center four inches of each specimen was used for the bond strength test, making the bond area approximately 2.5 by 4 inches.

3.4 Bond Strength and Durability Tests

Currently, there are no standard methods for determining the bond resistance of crack sealants. Here, a variation of the well known splitting cylinder test (ASTM C 496) to measure the tensile strength of concrete is used to obtain a relative comparison of the bond strength of crack sealants as shown in Fig. 3.3.3. This test is essentially the same as that used to form the cracks in the specimens. Figure 3.3.4 shows the calculated elastic stress distribution using finite element analysis in the direction perpendicular to the crack, for a specimen with a $\frac{1}{2}$ in. wide crack when loaded as shown in Fig. 3.3.1. The stresses are shown for an applied compressive load of one kip. It can be seen that the stress distribution is similar to that of a standard cylinder test, with tensile stresses developing over most of the crack depth, with compressive stresses developing only at the top and bottom of the crack. As the specimen deforms in the direction perpendicular to the crack, a sealant may either fracture or debond

from the crack walls. On the other hand, a sealant may be strong enough and a concrete fracture may occur instead. As a result, this test can provide an indirect, but a reasonable estimate of the relative performance and quality of the adherence of the sealant to concrete.

The equipment, setup, instrumentation and test procedure was the same as that used in the previous study and has been described elsewhere (Pincheira and Dorshorst, 2005).

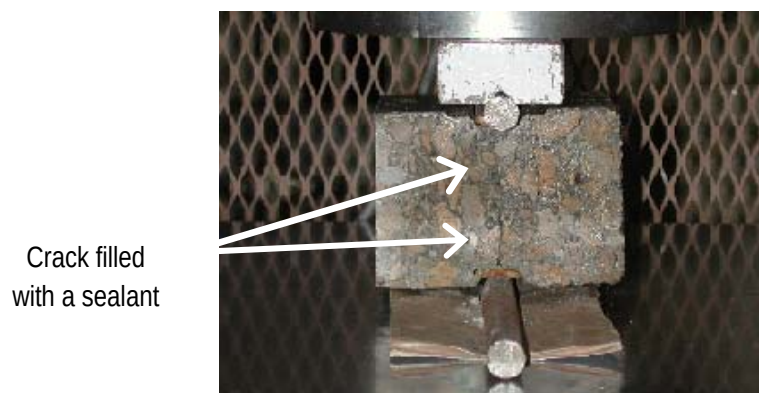


Figure 3.3.3 Setup used to test the bond strength of the crack sealant specimens

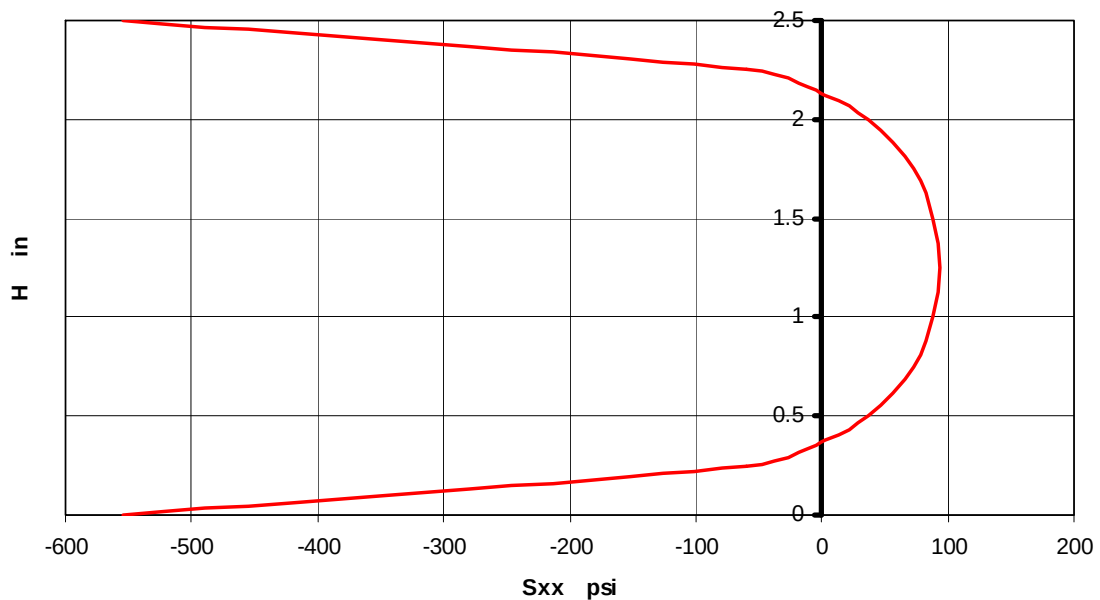


Figure 3.3.4 Elastic stress distribution over the crack depth in the direction perpendicular to the crack.

3.5 Depth of Penetration Tests

The depth of penetration of the sealants was measured by visually examining two cross-sections per specimen both with the naked eye and using a measuring magnifier. Figure 3.3.5 shows a cross section of a crack already filled with the sealant. The ability of the sealant to completely or only partially fill the crack was measured and recorded. In addition, if voids were present within the sealant, the shallowest depth at which the first void or air pocket appeared was also recorded. A second void depth was recorded if the void was significantly different in size or shape from the first void.



Figure 3.3.5 Cross section of a crack sealant specimen filled with a sealant

3.6 Freeze-thaw cycle tests

The durability of the sealants was measured by subjecting specimens to freeze-thaw cycles before being tested for the bond strength. Sealants severely affected by freeze-thaw cycles were expected to lose their ability to remain fully bonded to crack walls and exhibit reduced bond strength and a different failure mode.

The procedure to assess the influence of freeze-thaw cycles was the same as that used in the previous study and followed ASTM C 666 “Resistance of Concrete to Rapid Freezing and Thawing” with minor modifications. The specimen size required in ASTM C 666 was between 3 in. and 5 in. in width, depth or diameter, and between 11 in. and 16 in. in length. The sample containers in freeze-thaw apparatus at the WSMTL were fabricated to accommodate specimens

3 in. by 4 in. by 16 in. Therefore, a deviation from the specimen size called for in ASTM C 666 was required to test the durability of the crack sealant specimens, which measured 3 in. by 4 in. by 8 in.

Three hundred freeze-thaw cycles were performed in chambers at the WSMTL, where the temperature of the specimens was alternately lowered from 50°F to 0°F and raised from at 0°F to 50°F. While ASTM C 666 requires that 40°F be the maximum temperature during the thawing phase of the cycle, it was increased to 50°F based on concerns over specimens not fully thawing at 40 degrees F during previous studies performed at the WSMTL. Specimens were completely surrounded by water at all times during the cycles, which averaged about 5 hours long. Additionally, ASTM C 666 requires that specimens be removed from the freeze-thaw apparatus at regular intervals during the tests to measure length change and the fundamental transverse frequency. These tests are used to gauge the performance of the concrete due to freeze-thaw cycling, and since the goal of this study was to evaluate sealant performance, these intermediate tests were eliminated. Figure 3.3.6 shows one of the freeze-thaw chambers loaded with specimens at the WSMTL. At the conclusion of the freeze-thaw cycles specimens were removed from the chambers and allowed to dry. Within the next few days the specimens were prepared and tested for the bond strength as described previously in section 3.4.



Figure 3.3.6 Freeze-thaw chamber at the WSMTL loaded with crack sealant specimens

CHAPTER 4

Test Results and Discussion

4.1 Introduction

In this chapter, the data obtained from the bond strength and durability tests are presented and discussed. Based on the analysis of the test data and their performance, the sealants are ranked and assigned to a performance group category.

4.2 Test Results

4.2.1 Measured Concrete Properties

The methods used to measure the fresh and hardened concrete properties have been described elsewhere (Pincheira and Dorshorst, 2005). In this study, three concrete batches were required to fabricate the specimens. Figure 4.2.1 shows measured compressive strength obtained for these batches (three cylinders were tested for each batch).

The average compressive strength was 6390 psi, 6000 psi, 5710 psi, for the first, second and third batches, respectively. These values were all above the minimum required for strength (4000 psi), but most important, they compare very well with the strengths obtained in the previous study by Pincheira and Dorshorst (2005), which varied between 5630 psi and 6580 psi. Furthermore, the average measured strength of all batches cast in this and the previous study was 6189 with a standard deviation of 339 psi or 5.5%.

4.2.2 Depth of Penetration

The depth of penetration of the crack sealants was measured by visually examining the specimens both with naked eye and with a measuring magnifier. All of the sealants were able to penetrate the full depth of the crack (2 ½ in.) irrespective of the crack width. Some specimens, however, exhibited very small voids or air pockets within the sealant, or between the sealant and the face of the crack. The number and location of these air pockets were randomly distributed and did not show any consistent pattern for a given crack width or a

sealant type. As in the previous study, these voids were judged not to affect the behavior and performance of the sealants.

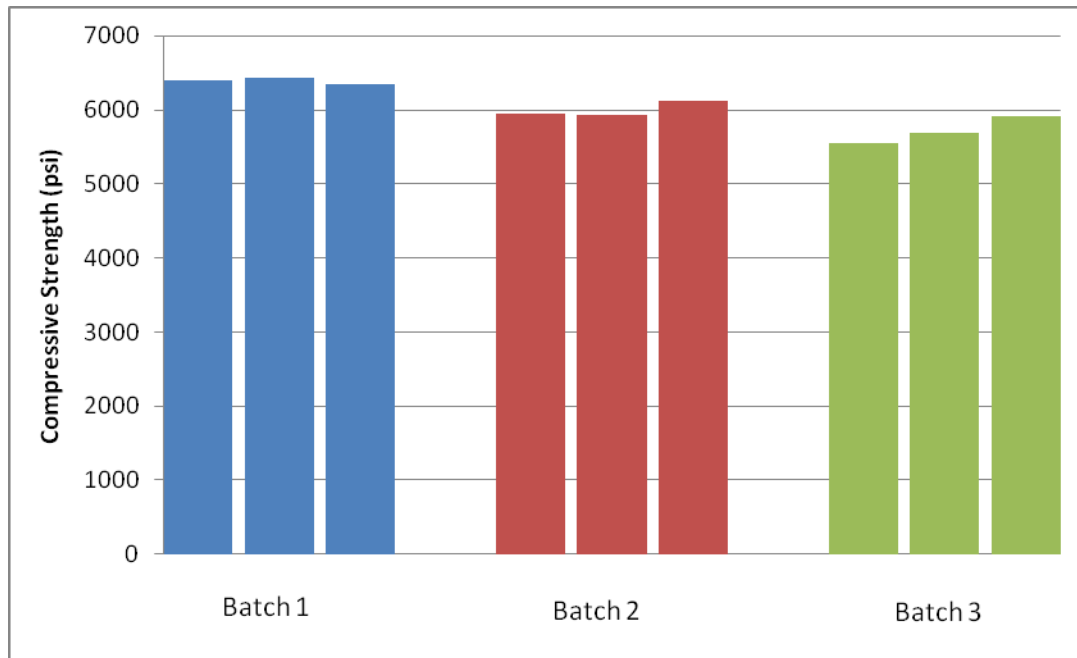


Figure 4.2.1 Measured compressive strength

4.2.3 Bond Strength and Durability Tests

Several failure modes were observed during the tests. These were divided into three basic categories: concrete failure, bond failure and sealant failure. A concrete failure was indicated by cracks primarily in concrete adjacent to the sealed crack. Such a failure mode was desirable as this was an indication that the sealant adhered well to the crack faces. An example of this failure mode is shown in Fig. 4.2.2. A bond failure was indicated by cracks in the sealant-concrete interface as shown in Fig. 4.2.3. A sealant failure was defined by cracks passing directly through the sealant without involvement of the adjacent concrete as illustrated Fig. 4.2.4. In addition, failure modes that involved combinations of one or more of the three aforementioned failure modes were also observed.

4.2.3.1 Hairline Crack Width Series ($\frac{1}{32}$ ")

The results for all sealants tested with hairline crack widths are shown in Table 4.2.1. In the table, the data obtained for specimens not exposed as well as those exposed to freeze-thaw cycles are shown. The data are also plotted in Figs. 4.2.5 for the specimens not exposed to freeze-thaw cycles and in Fig. 4.2.6 for specimens subjected to freeze-thaw cycles.



Figure 4.2.2 Example of a concrete failure.

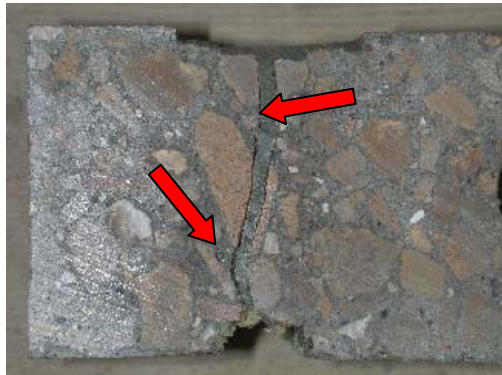


Figure 4.2.3 Example of a bond failure.



Figure 4.2.4 Example of a sealant failure.

Table 4.2.1 Summary of Hairline Crack Width Bond Strength Test Results

Sealers	Without F/T Cycles			With F/T Cycles			% Average Reduction Non F/T to F/T
	Bond Strength (lb)	Failure Mode*	Ave. Bond Strength (lb)	Bond Strength (lb)	Failure Mode*	Ave. Bond Strength (lb)	
Sikadur 55 SLV	8564	C	8560	6147	B	6020	30
	8665	C		5071	C,B		
	10234	C		5248	B		
	6793	C		7614	C		
Dural 335	9387	C	8329	7789	C,B	6599	21
	9759	C		7933	C,B		
	8296	C		7518	C		
	5872	C		3155	C		
Sikadur 52	8717	B	7350	3315	C,B	3845	48
	6583	C,B		3713	B		
	6425	C		4191	C		
	7676	C		4160	C		
Degadeck Crack Sealer	5867	C	5585	3182	B	3902	30
	6655	C		2853	C		
	4624	C		4667	C,B		
	5192	C		4901	B		
Denedeck Crack Sealer	4870	C	5191	5795	B	4152	20
	5889	C		2632	B		
	5227	C		6596	C,B		
	4777	C		1586	B		
TK-9030-N	4755	C	4154	3942	C,B	3373	19
	4548	C		3692	C,B		
	2711	C		2479	C,B		
	4601	C		3377	C,B		

C = Concrete B = Bond S = Sealant

The results show a significant variation in strength among sealants tested with hairline crack widths. The average strength ranged from 2,711 lbs. to 10,234 lbs. for specimens not exposed to freeze-thaw cycles, while the average strength for specimens subjected to freeze-thaw cycles ranged from 1,586 up to 7,789 lbs. Note that for specimens not exposed to freeze-thaw cycles a concrete failure mode was observed for all sealants but one specimen sealed with Sikadur 52, which showed a combined concrete and bond failure mode.

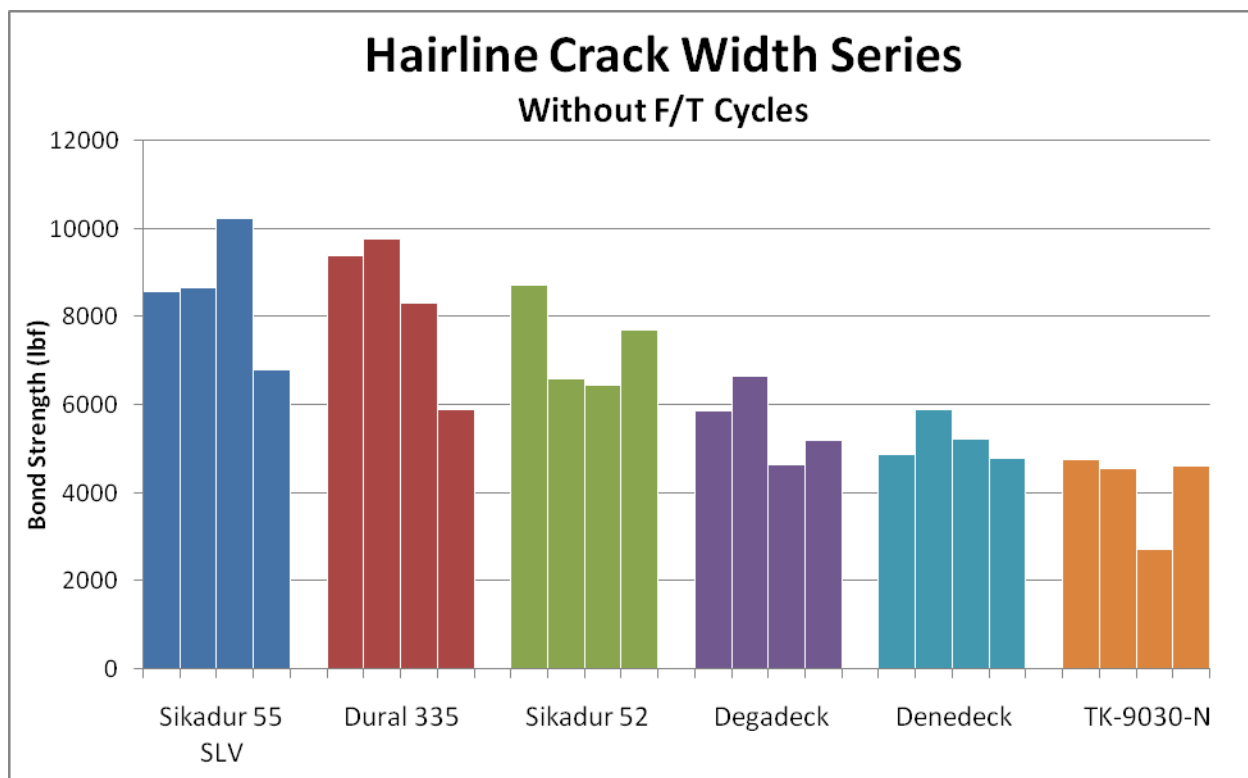


Figure 4.2.5 Bond Strength of Specimens Not Exposed to Freeze-Thaw Cycles – Hairline Crack Width.

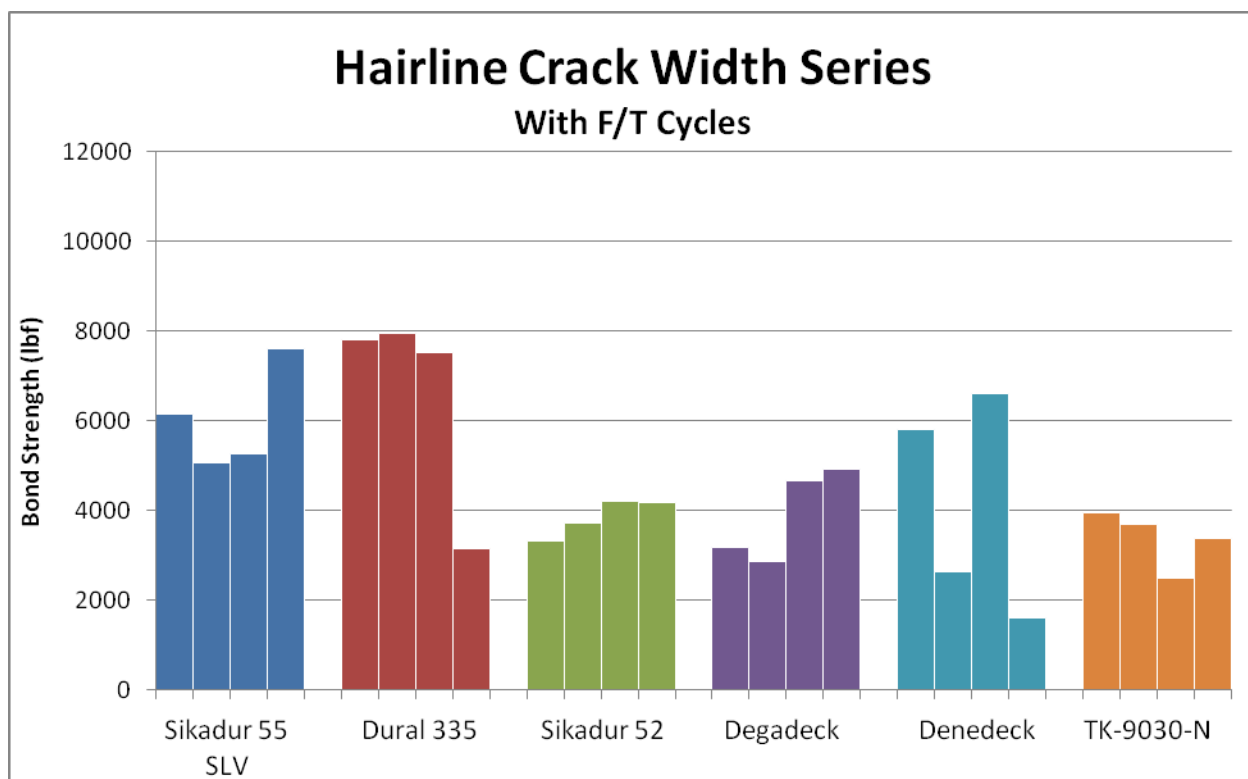


Figure 4.2.6 Bond Strength of Specimens Exposed to Freeze-Thaw Cycles – Hairline Crack Width.

As mentioned above, the average measured concrete strength of all the batches has a standard deviation of 5.5%. Although all specimens exhibited a concrete failure, the large variation in the measured bond strength cannot be attributed solely to different concrete strengths among the batches. A plausible explanation to this result is the lower stiffness of the sealant material and misalignment of the randomly created crack with respect to the applied load. Nonetheless, the lower strength of some specimens in this case, however, should *not* be construed as a poor performance of the sealer as a concrete failure rather a bond or sealant failure is an indication of good adherence and strength of sealant to the crack surface.

All specimens experienced a reduction in strength when exposed to freeze-thaw cycles. The last column in Table 4.2.1 shows the reduction in the average measured strength due to freeze-thaw cycles. It can be seen that the sealants experienced a decrease in bond strength ranging between 19 and 48 percent after being subjected to freeze-thaw cycles. Also note that some specimens showed a combined concrete and bond failure or bond failures alone. However, no sealant failures were observed.

4.2.3.2 Narrow crack width series ($\frac{1}{16}$ ")

Table 4.2.2 shows the test results obtained from the specimens with narrow crack widths. The data are also plotted in Figs. 4.2.7 and 4.2.8 for the specimens not exposed to freeze-thaw cycles and those subjected to freeze-thaw cycles, respectively. The results show that strength ranged from an average of 1,450 lbs to 9,350 lbs for specimens not subjected to freeze-thaw cycles, and from 637 lbs to 6,913 lbs for those subjected to freeze-thaw cycles. Similar to specimens tested with hairline crack widths, all sealants experienced a reduction in strength when exposed to freeze-thaw cycles. Most sealants show a decrease in strength of approximately 30%, with the smallest reduction of about 10%.

As was expected, all specimens exhibited some reduction in strength with respect to the results obtained for the specimens with hairline crack widths. More important, however, a greater number of concrete-bond failures were observed for specimens with and without exposure to freeze-thaw cycles. Furthermore, under freeze-thaw cycles a bond mode failure was predominant in the specimens sealed with Degadeck and Denedeck. Pro-Poxy 50 showed a

combination of concrete and bond or sealant failures with and without exposure to freeze-thaw cycles.

Table 4.2.2 Summary of Narrow Crack Width Bond Strength Test Results

Sealers	Without F/T Cycles			With F/T Cycles			% Average Reduction Non F/T to F/T
	Bond Strength (lb)	Failure Mode*	Ave. Bond Strength (lb)	Bond Strength (lb)	Failure Mode*	Ave. Bond Strength (lb)	
Sikadur 55 SLV	6588	C	7994	5074	C	5876	26
	8704	C		6201	C		
	9126	C,B		6913	C		
	7558	C		5316	C,B		
Dural 335	6238	C	4544	1711	B	2952	35
	6347	C		7178	C		
	3906	C,B		2280	B		
	1683	C		637	B		
Sikadur 52	6716	C,B	6140	4500	C,B	4352	29
	5183	C,B		2549	B		
	6987	C		5530	C		
	5674	C,B		4828	C		
Degadeck	5796	C	5680	4612	B	3521	38
	5046	C		4043	C,B		
	5648	C,B		2203	B		
	6230	C		3226	B		
Denedeck	4483	C	5101	5552	B	3695	28
	5595	C,B		5643	B		
	5584	B		2309	B		
	4743	C		1274	B		
TK-9030-N	3643	C,B	3325	3323	C,B	2968	11
	2714	C,B		2864	C,B		
	3095	C		3450	C,B		
	3846	C		2235	C,B		
Pro-Poxy 50	1450	C,S	6014	5418	C,S	4658	23
	6926	C		6567	C,S		
	9350	C		3288	C,S		
	6328	C,B		3359	C,B		
Pro-Poxy 100	2863	C	4296	4192	C	3860	10
	4231	C		3958	C		
	6794	C		3429	C		
	3296	S,B		-	-		

C = Concrete B = Bond S = Sealant

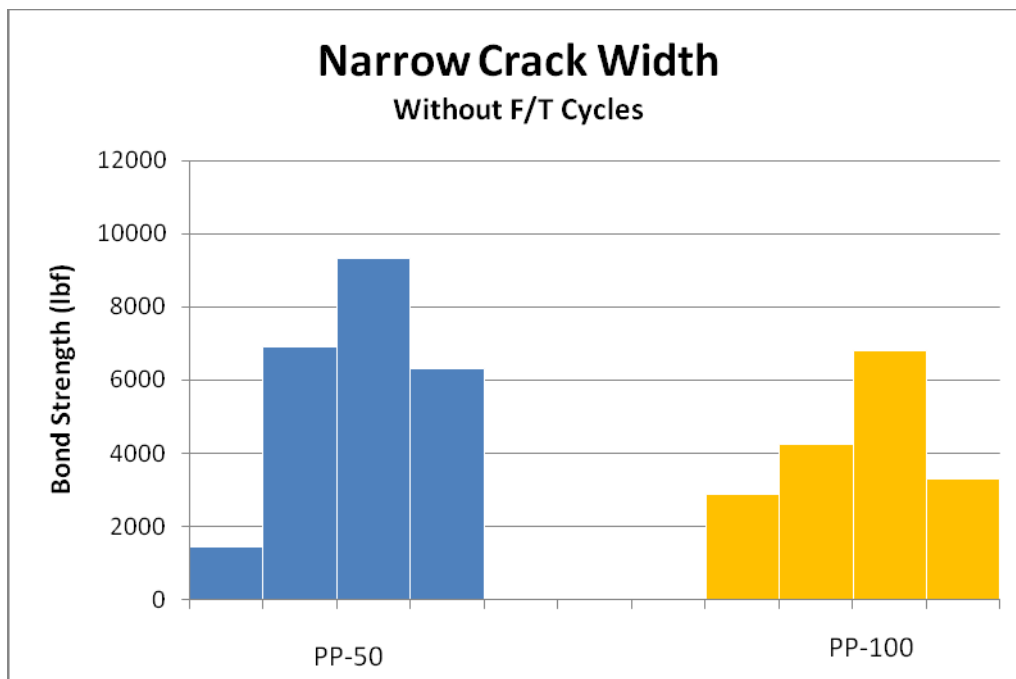
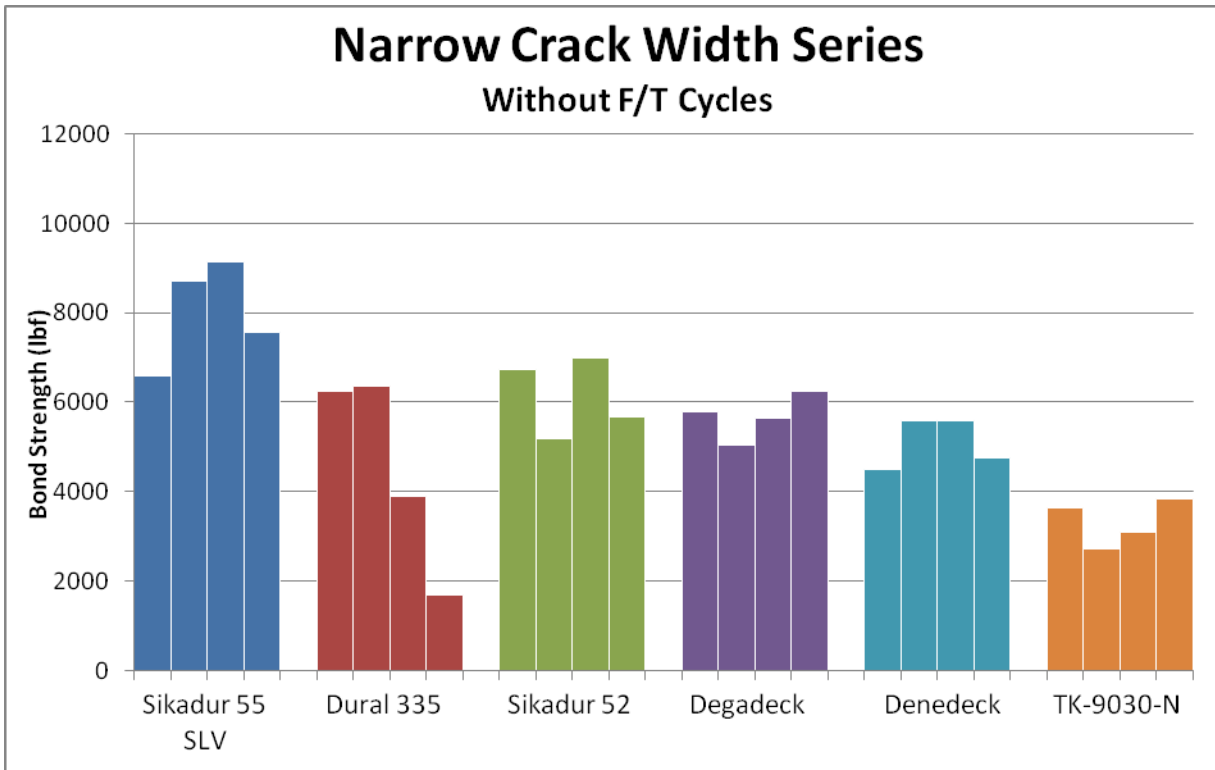


Figure 4.2.7 Bond Strength of Specimens Not Exposed to Freeze-Thaw Cycles – Narrow Crack Width.

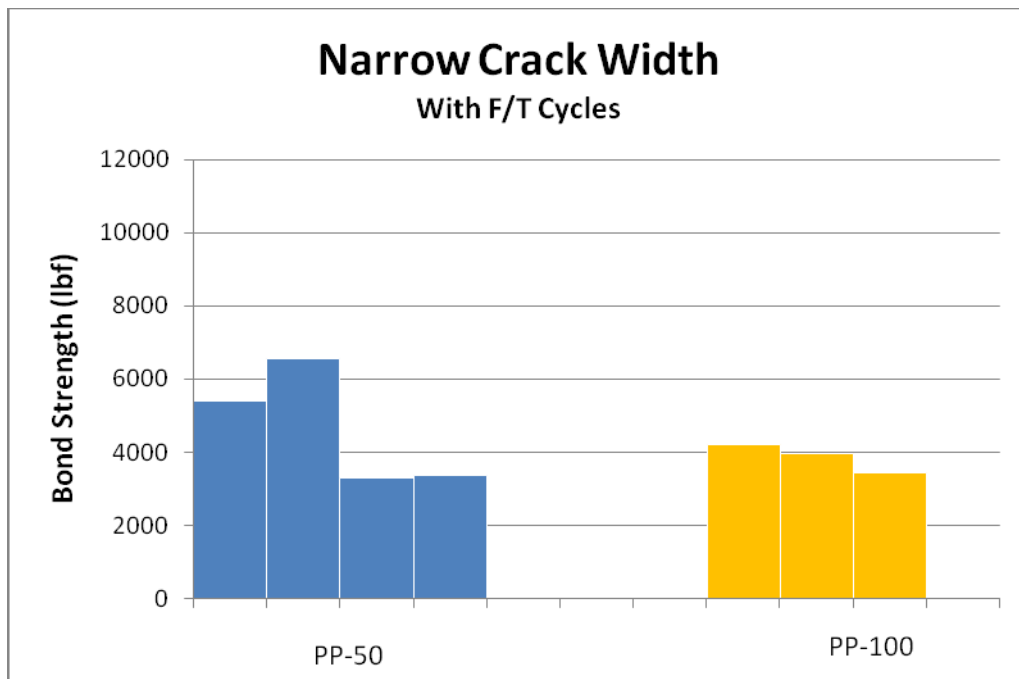
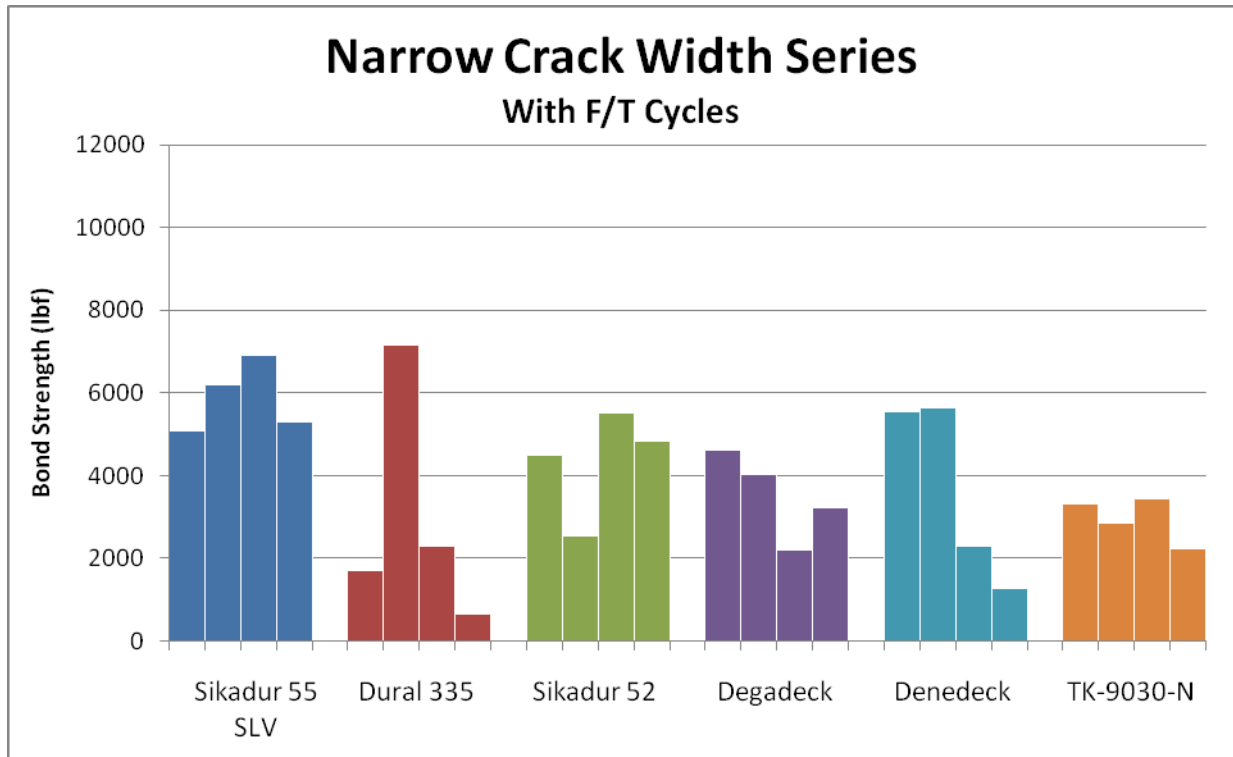


Figure 4.2.8 Bond Strength of Specimens Exposed to Freeze-Thaw Cycles – Narrow Crack Width.

4.2.3.3 Medium crack width series ($\frac{1}{8}$ ")

Table 4.2.3 shows the results of the tests performed on specimens with medium crack widths. The average bond strength for specimens not exposed to freeze-thaw cycles ranged from 2,838 lbs to 7,705 lbs, and from 905 lbs to 7,207 lbs for those subjected to freeze-thaw cycles. The results are also plotted in Figs. 4.2.9 and 4.2.10. Sikadur 55 SLV provided the highest bond strength among all sealants tested with medium crack widths, for specimens exposed and not exposed to freeze-thaw cycles. On the other hand, Dural 335 showed a consistent and significant reduction in strength with exposure to freeze-thaw cycles with respect to the results obtained with hairline crack widths.

Under freeze-thaw cycles, Sikadur 52, Degadeck, Denedeck, TK-9030-N or Pro-Poxy 100 showed predominantly bond failures, an indication of the deterioration of the adherence of the sealant material to the face of the crack with freeze-thaw cycles. Sikadur 55 SLV, on the other hand, exhibited predominantly concrete failures with and without exposure to freeze thaw cycles, with only minor reductions in strength.

4.2.3.4 Wide crack width series ($\frac{1}{5}$ ")

The results of the bond strength tests for all sealants tested with wide crack widths are shown in Table 4.2.4, and in Figs. 4.2.11 and 4.2.12. The results show a large variation in strength and failure mode among the specimens with wide crack widths. The average strength ranged from 1,248 lbs to 6,176 lbs for specimens not exposed to freeze-thaw cycles, while the average strength for specimens subjected to freeze-thaw cycles ranged from 0 lbs up to 3,653 lbs. It can be seen that most sealants experienced up to about 70% decrease in strength after being subjected to freeze-thaw cycles.

The predominant failure mode for specimens without exposure to freeze-thaw cycles sealed with Sikadur 55, Denedeck or TK-9030-N was concrete splitting. However, companion specimens with these same sealants subjected to freeze-thaw cycles, failed predominantly by bond or a sealant failure. The other sealants, Dural 335, Sikadur 52, Degadeck and Pro-Poxy 204, on the other hand, showed predominantly bond or sealant failure with and without exposure to freeze-thaw cycles.

Table 4.2.3 Summary of Medium Crack Width Bond Strength Test Results

Sealers	Without F/T Cycles			With F/T Cycles			% Average Reduction Non F/T to F/T
	Bond Strength (lb)	Failure Mode*	Ave. Bond Strength (lb)	Bond Strength (lb)	Failure Mode*	Ave. Bond Strength (lb)	
Sikadur 55 SLV	4096	C	6321	6388	C	5572	12
	7705	C		7207	C		
	7458	C		3831	B		
	6023	C		4860	C		
Dural 335	4901	C	3700	4723	B	3268	12
	3185	C,S		905	B		
	3874	C		5344	C		
	2838	C		2101	C		
Sikadur 52	5991	C,B	6012	2497	B	2463	59
	5968	C		2456	B		
	6529	C,B		1377	B		
	5558	C		3521	B		
Degadeck	3877	C	4129	4820	C,B	3625	12
	4690	C,B		3380	B		
	3169	B		2985	B		
	4780	B		3315	B		
Denedeck	6019	C,B	5257	3602	B	2498	52
	6454	C,B		1832	B		
	4926	C,B		2884	B		
	3630	B		1675	B		
TK-9030-N	4083	C	4518	2848	B	2714	40
	3197	C		3158	C		
	6479	C		2686	B		
	4311	C		2162	B		
Pro-Poxy 100	5174	C	3860	1753	B	3137	19
	3187	C		1251	B		
	4601	C		6408	C,B		
	2878	C		-	-		

C = Concrete B = Bond S = Sealant

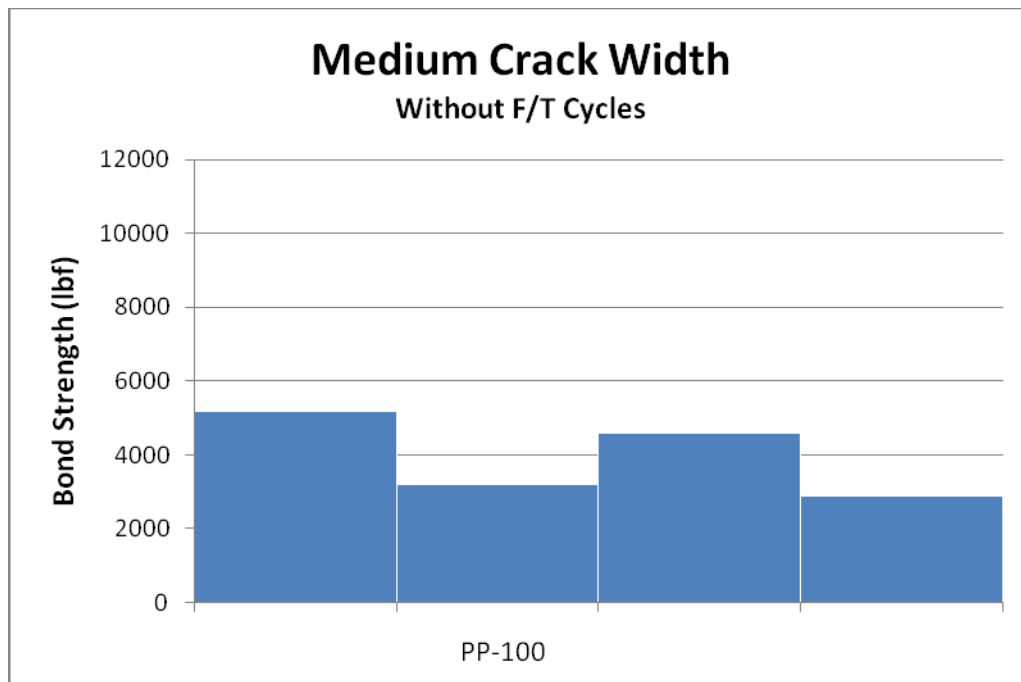
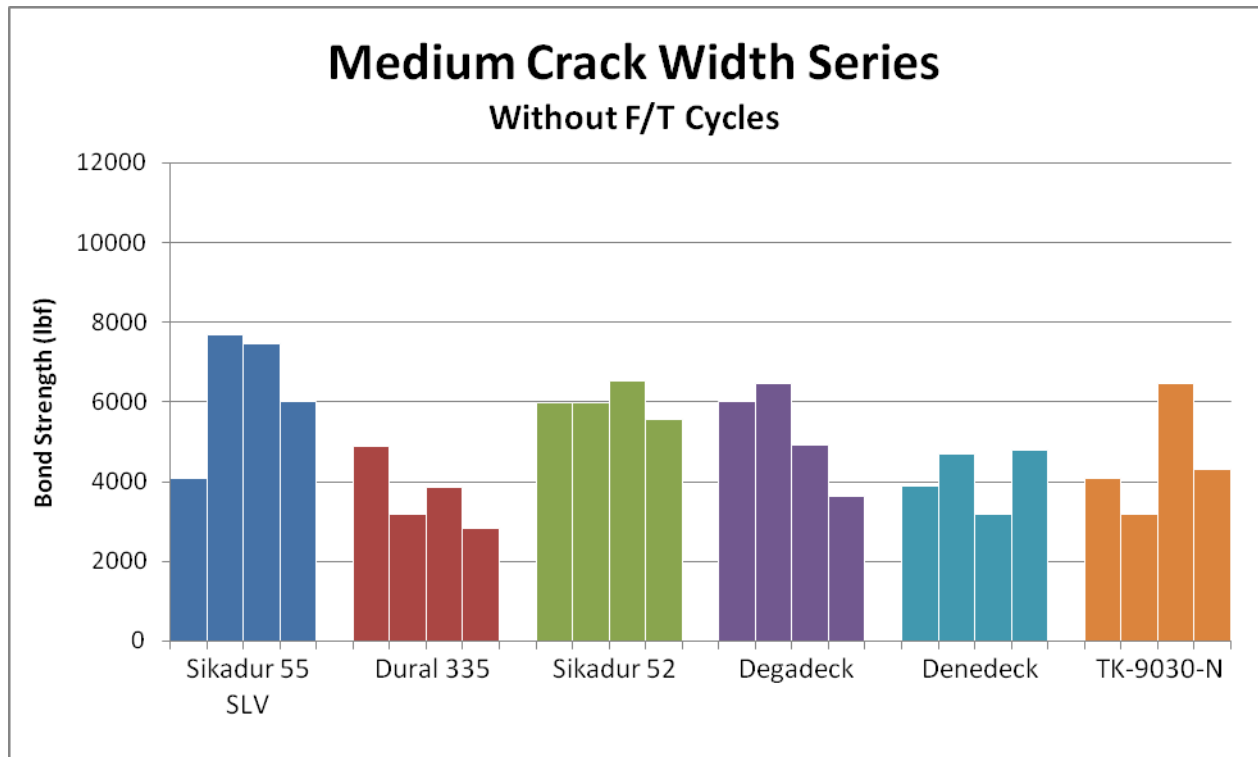


Figure 4.2.9 Bond Strength of Specimens Not Exposed to Freeze-Thaw Cycles – Medium Crack Width.

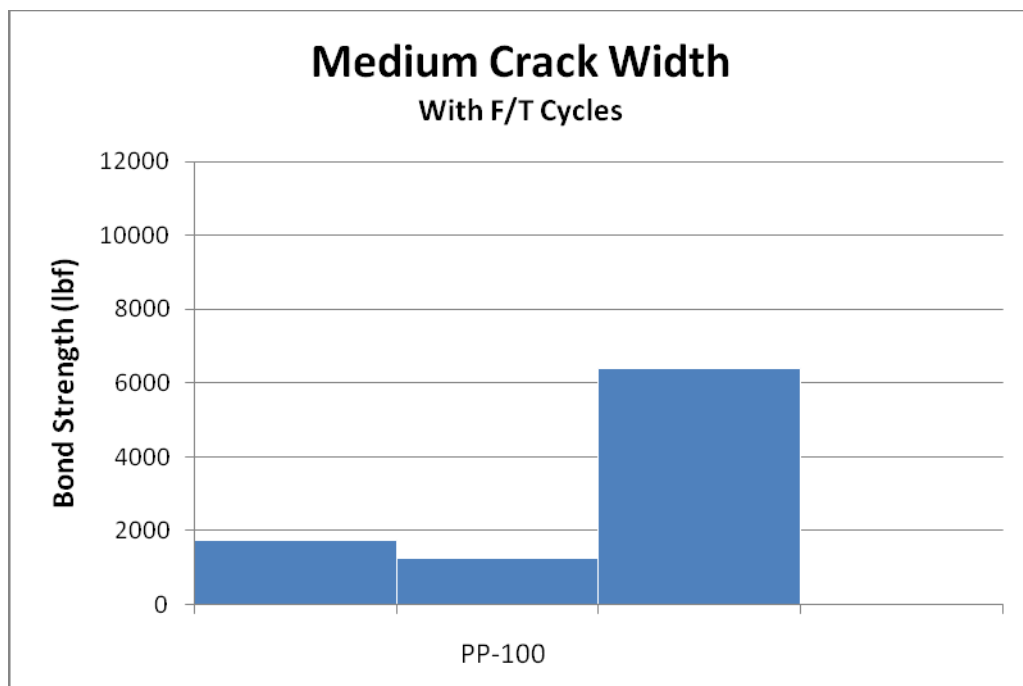
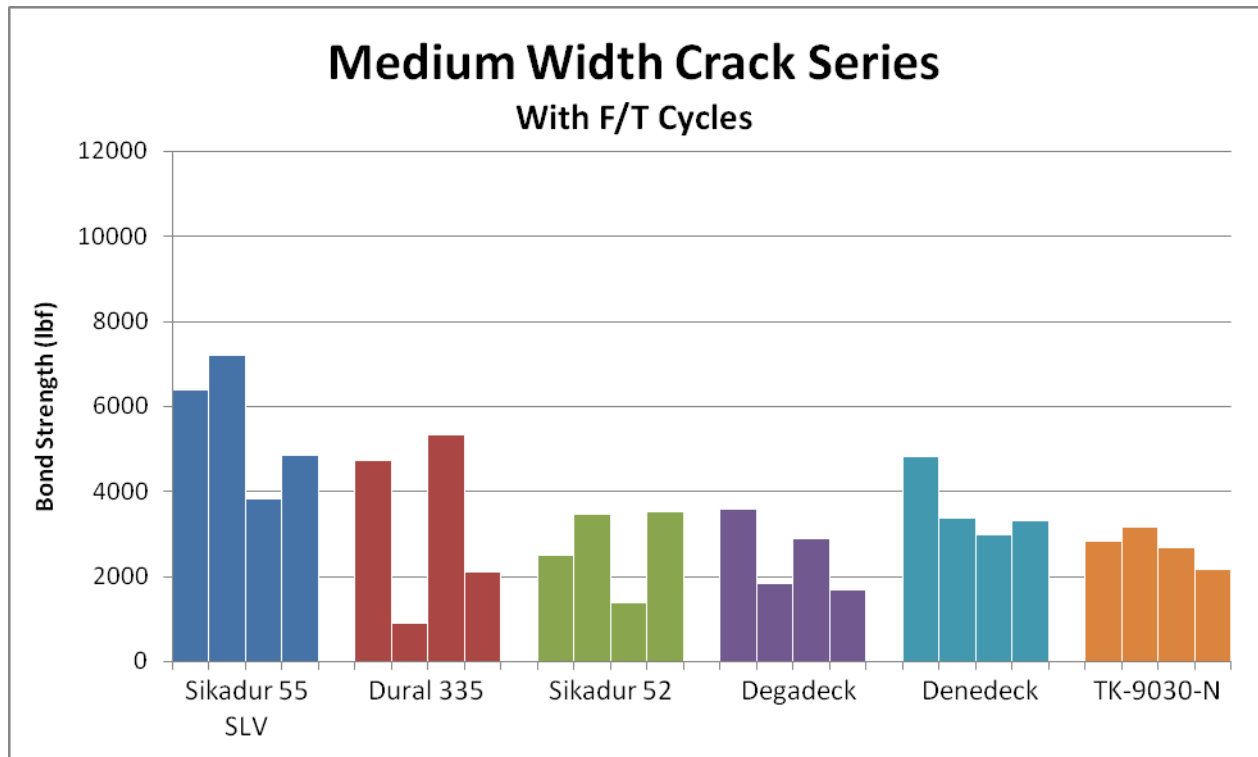


Figure 4.2.10 Bond Strength of Specimens Exposed to Freeze-Thaw Cycles – Medium Crack Width.

Table 4.2.4 Summary of Wide Crack Width Bond Strength Test Results

Sealers	Without F/T Cycles			With F/T Cycles			% Average Reduction Non F/T to F/T
	Bond Strength (lb)	Failure Mode*	Ave. Bond Strength (lb)	Bond Strength (lb)	Failure Mode*	Ave. Bond Strength (lb)	
Sikadur 55 SLV	6176	C	4685	3653	C	2442	48
	1961	S		2112	B,C		
	4234	C		387	S		
	6368	C		3616	S		
Dural 335	1741	C	2014	769	S	633	69
	1081	S		0	S		
	2073	S		1077	B		
	3161	S		687	B		
Sikadur 52	3609	B	3429	3181	B	1508	56
	3263	S		260	B		
	3969	S		201	B		
	2875	C,B		2390	C		
Degadeck	2494	B	3583	1892	B	930	74
	4316	C		419	B		
	3959	B		949	B		
	3561	B		460	B		
Denedeck	1248	C	1953	1592	B	772	60
	1226	C		754	B		
	3131	B		331	B		
	2208	C		409	B		
TK-9030-N	3218	C,B	3625	2580	B	2803	23
	3959	C		2697	B		
	2957	C		2933	C,B		
	4366	C		3132	C,B		
Pro-Poxy 204	1312	C,S	1904	1380	B,S	1679	12
	1401	C,B		800	C,B		
	2486	C,S		3421	C,B		
	2420	B		1113	B,S		

C = Concrete B = Bond S = Sealant

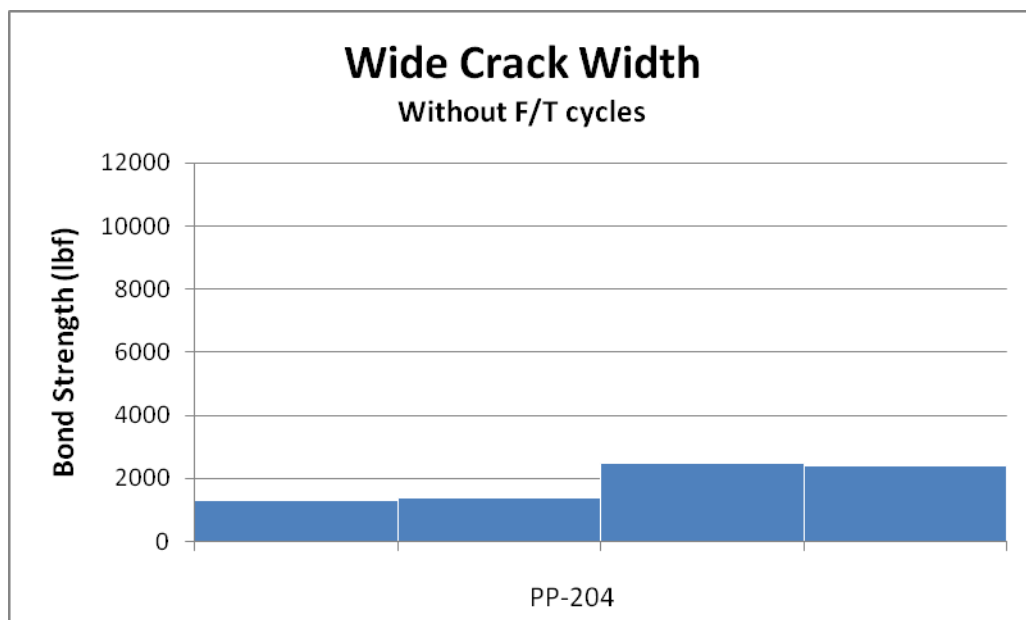
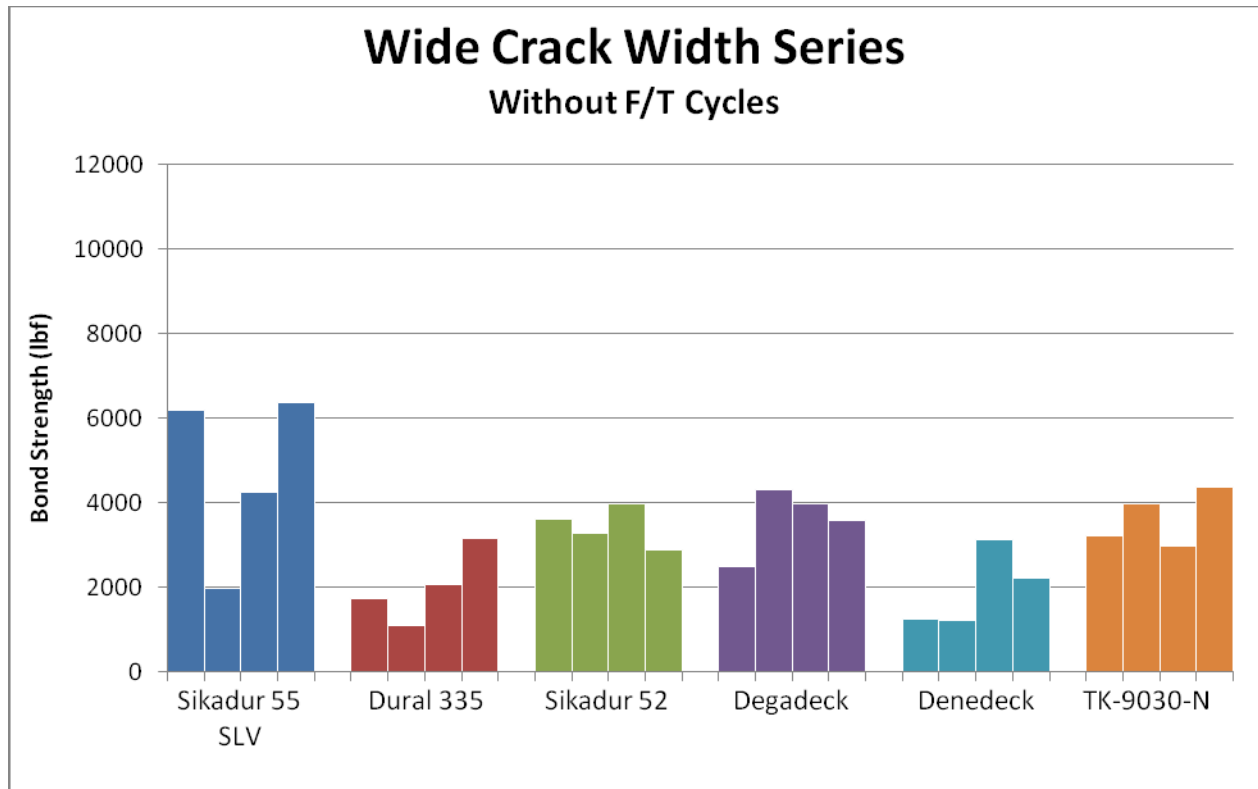


Figure 4.2.11 Bond Strength of Specimens Not Exposed to Freeze-Thaw Cycles – Wide Crack Width.

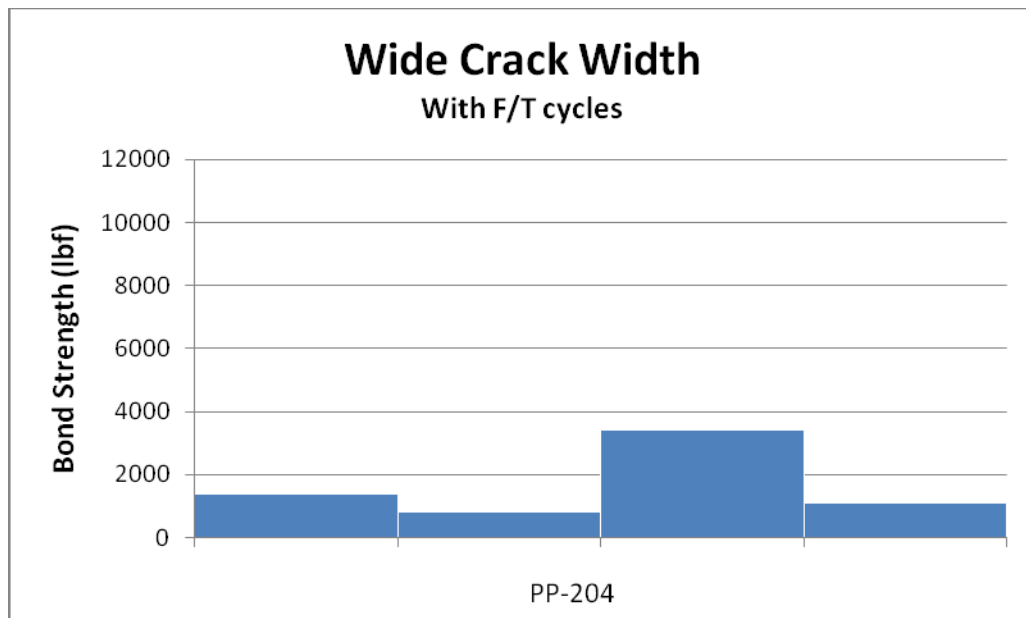
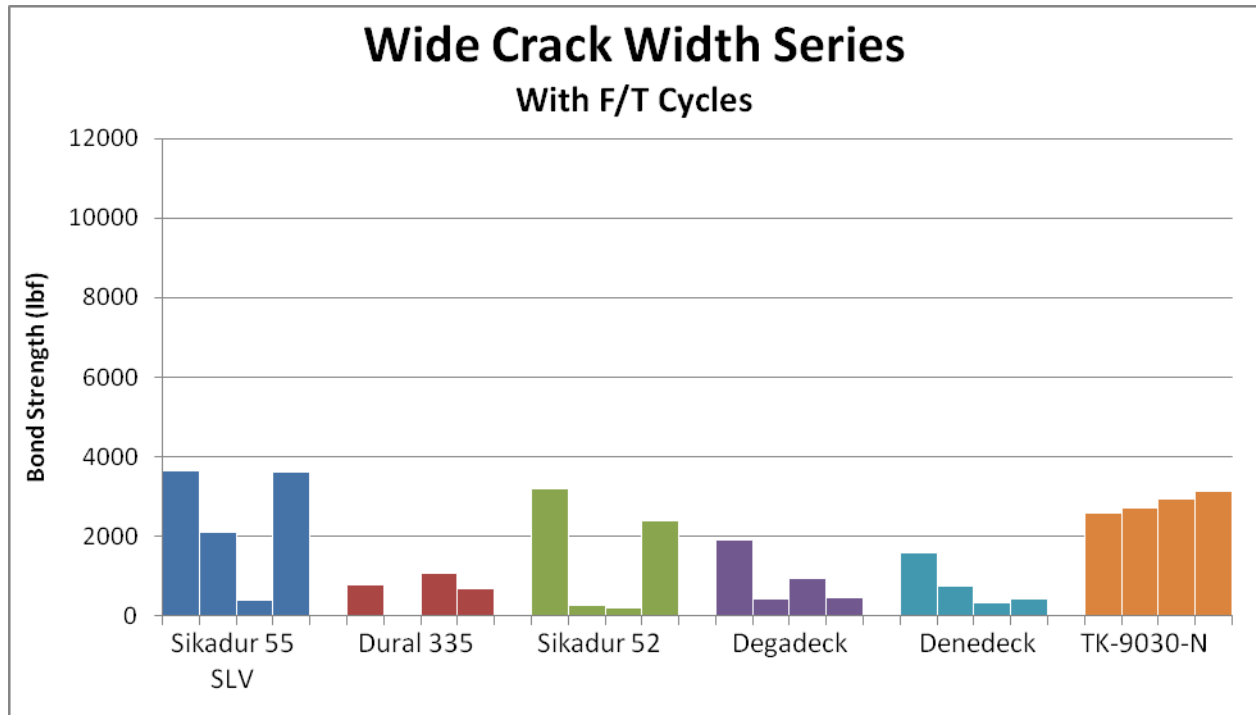


Figure 4.2.12 Bond Strength of Specimens Exposed to Freeze-Thaw Cycles – Wide Crack Width.

4.3 Discussion

4.3.1 Failure Mode

4.3.1.1 General Observations

Irrespective of the crack width, the same general trends were observed among sealants tested for a given crack width, with a few exceptions. In the following, the trends observed only in specimens with hairline cracks are discussed. However, specimens with larger crack widths showed similar trends. Any other unique trends specific to a particular crack width are also discussed.

Several failure modes were observed during the bond strength tests of specimens with hairline crack widths as shown previously in Table 4.2.1 for specimens not exposed to freeze-thaw cycles, almost all of them show a concrete failure. The measured bond strength showed considerable scatter for a given sealant and also among the sealants exhibiting concrete failures. The scatter of the data is attributed to the fact that each specimen had a different and unique crack. As a result, a different resistance was expected.

In general, sealants which displayed primarily concrete failures had the highest bond strengths, followed by a combination of concrete and bond failures. Bond failures were generally associated with lower bond strengths, and the lowest bond strengths were associated with sealant failures. Concrete failures are desirable because it means that the sealant adhered well to the crack faces and was strong enough to induce failure of the concrete rather than of the sealant. Thus, sealants which exhibit primarily concrete failures regardless of the crack width can be considered to provide adequate bond strength.

4.3.1.2 Influence of crack width

It may be observed that nearly all specimens exhibited concrete failures among the strongest sealants tested with hairline crack widths. As the crack width increased, however, concrete failures became less common, and became a combination of concrete and bond failures. As the amount of sealant is increased within a specimen (i.e., as the crack width is increased), the area enclosing the crack and sealant becomes weaker in comparison with the

surrounding concrete, because the amount of sealant is large enough to significantly impact the strength and stiffness of the cross section. As a result, a larger number of bond and/or sealant failures can be expected occur with increasing crack width.

4.3.2 Effect of freeze-thaw cycles

As was expected, all sealants experienced a reduction in bond strength when subjected to freeze-thaw cycles. However, the reduction in strength varied for each sealant and crack width as described previously. Sikadur 55 SLV consistently showed the highest average bond strength when exposed to freeze-thaw cycles. Furthermore, it showed predominantly concrete or bond failures with no sealant failures except at wide crack widths. TK-9030-N, though with lower average strength, also showed predominantly concrete or bond failures when exposed to freeze-thaw cycles, with no sealant failures. Degadeck, and Denedeck showed large variations in the failure mode and significant reductions in strength under freeze-thaw cycles, but with no sealant failures. Sikadur 52 also showed large variations in strength but with smaller strength reductions. Dural 335 showed consistent and moderate reductions in strength for crack widths up to a medium size. For wide cracks, significant reductions in strength were observed and in one instance no strength after freeze-thaw cycles.

As mentioned in section 3.2, the Pro-Poxy type sealants, were suitable specific crack widths and therefore were only tested in their own crack width category. Pro-Poxy 100 showed very good performance for the narrow crack width both with and without exposure to freeze-thaw cycles. On the other hand, the performance of Pro-Poxy 50 was not as good as Pro-Poxy 100 for narrow crack widths, under freeze-thaw cycles. For medium cracks, Pro-Poxy 100 showed wide scatter, low strength and mainly bond failures under freeze-thaw cycles. For wide cracks, Pro-Poxy 204 showed significant reductions in strength under freeze-thaw cycles with many bond and sealant failures.

These data illustrate the scatter that exists in the failure mode, strength and overall performance of the sealants when subjected to freeze-thaw cycles. Sealants can perform well in a range of crack widths when not exposed to freeze-thaw cycles, but suffer severe reductions in strength at certain crack widths when exposed to freeze-thaw cycles. Therefore, sealant

performance should be judged at specific crack widths, as exposure to freeze-thaw cycles may impact sealants more at certain crack widths.

4.3.3 Acceptance Criteria and Sealant Performance

All of the sealants tested in this study were able to fill the cracks over the entire depth without difficulty. As a result, all of the sealants are considered equally good in terms of their ability to fill a crack of any size.

The ability of the sealants to prevent the ingress of water and deicing salts in the long term was assessed indirectly by measuring the relative strength and failure mode in bond strength tests of specimens with and without exposure to freeze-thaw cycles. Ideally, optimum performance would be obtained for a sealant that exhibited only concrete failures with and without exposure to freeze-thaw cycles for all of the crack widths considered. This means that a sealant can maintain its adherence to the concrete under severe exposure conditions and deformations, prior to cracking of adjacent concrete. A bond or sealant failure is indicative of a premature loss of adherence to the concrete or failure of the sealant itself.

The data show that no single sealant or group of sealants exhibited such optimum, ideal performance over the entire crack width range, with or without exposure to freeze-thaw cycles. However, many showed excellent or very good performance over a wide range of cracks. Some general observations about the performance are described below:

1. All are excellent or very good products within the crack width range specified by the manufacturer. The lower performance observed for some sealants occurred for crack widths outside the range specified by the manufacturer. An exception to this result is Pro-Poxy 204 which showed the lowest performance in the wide crack width category (note that this product was selected during the course of this study and had not been tested before)
2. Sikadur 55 SLV showed primarily concrete failures with minor reductions in strength due to freeze-thaw cycles for the entire crack width range, except for wide cracks ($>1/5^{\text{th}}$ in. wide). A similar performance was observed for Pro-Poxy 100 for narrow cracks.

3. Degadeck, Denedeck, and TK-9030-N showed predominantly concrete failures without exposure to freeze-thaw cycles, but many bond failures under freeze-thaw cycles over the entire crack width range. A similar performance was observed for Sikadur 52, except for wide cracks where some sealant failures were observed with and without exposure to freeze-thaw cycles.
4. Dural 335 showed concrete or bond failures for hairline and narrow crack widths. Its performance decreased significantly for medium and wide cracks where many sealant failures were observed.

Based on these observations and using the ideal, optimum performance as a benchmark to establish a relative performance among the sealants studied, each sealant was assigned to a performance category as shown in Table 4.3.1. In the table, sealants with a comparable performance were assigned to a given performance category as follows. Those exhibiting the best performance were assigned to Category I, sealants with the second best performance to Category II, and so forth. Sealants with lowest relative performance were assigned to Category IV.

Table 4.3.1 Summary of Crack Sealant Performance

Product Name	Performance Group Category
Sikadur 55 SLV	I
TK-9030-N Degadeck Denedeck Pro-Poxy 50* Pro-Poxy 100**	II
Sikadur 52	III
Dural 533 Pro-Poxy 204***	IV

* tested only for narrow cracks

** tested only for narrow and medium cracks

*** tested only for wide cracks

Sikadur 55 was assigned to Category I because exhibited consistently concrete failures with and without exposure to freeze-thaw cycles and with minor reductions in strength for

hairline, narrow and medium crack widths. While its performance decreased for wide cracks, it emerged as the best product for most of the crack widths that may be encountered in practice. This product, however, is expensive and requires more time to open to traffic than other products.

TK-9030-N, Degadeck, Denedeck, Pro-Poxy 50 and Pro-Poxy 100 were all placed in the same category because they exhibited similar performance for hairline, narrow and medium crack widths. However, TK-9030-N showed an overall better performance than the other products and thus it was placed at the top of the list in the Category II products.

Sikadur 52 showed good performance for hairline and narrow crack widths, but showed significant reductions in strength for medium crack widths under freeze-thaw cycles as well as sealant failures for wide cracks.

Dural 335 appears to be a good product for hairline and narrow crack widths (the range specified by the manufacturer). Its performance deteriorated significantly for the wider cracks, especially for wide cracks and therefore it was assigned to Category IV. Pro-Poxy 204 exhibited a relatively lower performance than all of the other sealants in the wide crack width category.

4.3.4 Recommendations

Based on the performance assessment criteria presented above, the sealants assigned to Category I or II are recommended for use for all crack widths, with the caveat that a lower performance may be expected for wide crack widths. Sealants assigned to Categories III and IV are not recommended for crack widths outside of the range of crack widths specified by the manufacturer.

CHAPTER 5

Main Findings and Conclusions

5.1 Main Findings

- a) All of the sealants tested in this study were able to fill the cracks over the entire depth without difficulty. As a result, all of the sealants are considered equally good in terms of their ability to fill a crack of any size.
- b) All of the products tested in this study were found to have excellent or very good performance within the crack width range specified by the manufacturer. When lower performance was observed, it generally occurred for crack widths outside the range specified by the manufacturer. An exception to this result was Pro-Poxy 204 which showed substandard performance when compared to the other sealers.

5.2 Conclusions

Based on the test results and the assessment of the sealants considered in this study, the following conclusions may be drawn:

Sikadur 55 SLV was found to be the best performing sealant overall, followed by TK-9030-N, Degadeck, Denedeck which also showed very performance. Therefore, all of these products are recommended for use in the entire range of crack widths, i.e., hairline, narrow, medium and wide cracks. The remaining products tested in this study are recommended for use only within the crack width specified by the manufacturer.

5.3 Recommendations for Future Work

This investigation included laboratory tests of clean, i.e., free of debris, gravity fed sealed cracks. Under these conditions, all of the sealants were able to fill the cracks over the entire depth (3 in. in this study). In practice, however, cracks can be expected to be filled with debris and vary widely in width over the depth and over its length. The ability of a sealant to

fully penetrate and adequately seal the crack may depend strongly on the ability to properly clean the debris from the crack and to adequately apply the product. It is therefore recommended that a medium to long term study of crack sealants be conducted. The study could include the two or three of the best performing sealants to be applied to existing decks, by monitoring the various cleaning and application procedures that may be used in practice.

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