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FINAL REPORT ~ FHWA-OK-23-03

EVALUATING THE EXPECTED LIFE AND RECOATING OF SILANE WATER REPELLANT TREATMENTS ON BRIDGE DECKS

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September 2023

OKLAHOMA
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EVALUATING THE EXPECTED LIFE AND RECOATING OF SILANE WATER REPELLANT TREATMENTS ON BRIDGE DECKS

FINAL REPORT
ODOT Research Project Number 2287

Submitted to:
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16. ABSTRACT

Cracks allow outside chemicals to penetrate concrete and cause corrosion of the rebar. This work examines the performance of nine silane products with different properties. These products are used to penetrate through the crack and waterproof the concrete around the crack which slows the penetration of outside chemicals. The performance of the nine products are tested to determine their ability to create a waterproof layer around the crack. The results show that undiluted silane products with larger molecular formula such as Isobutyl triethoxy silane and octyl triethoxy silane can coat a large percentage and can penetrate deep into the concrete, creating the waterproof layer for cracks that are as small as 0.002”. Moreover, this work also examines the performance of seven repair materials in their ability to prevent outside chemicals from penetrating the cracks. The performance of the repair materials is checked by testing how long it takes for the water to penetrate different crack sizes. The results show that silane performs well in cracks smaller than 0.011 inches, Methacrylates performs well in cracks smaller than 0.019 inches, epoxies perform well in cracks smaller than 0.030 inches, the cracks treated with silane first and then epoxy perform well in cracks smaller than 0.036 inches, and the mix of bifunctional silane and epoxy performs well in cracks smaller than 0.050 inches.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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1.0 INTRODUCTION

Society is searching for a way to increase the durability of reinforced concrete structures. One important topic that will improve the durability of concrete is to reduce the impact of cracks. Cracks are fast pathways for outside chemicals such as chlorides to penetrate and reach the steel. If outside chemicals such as chloride reach the steel, they can cause corrosion which will cause additional cracking [1]. This process is outlined in Figure 1.

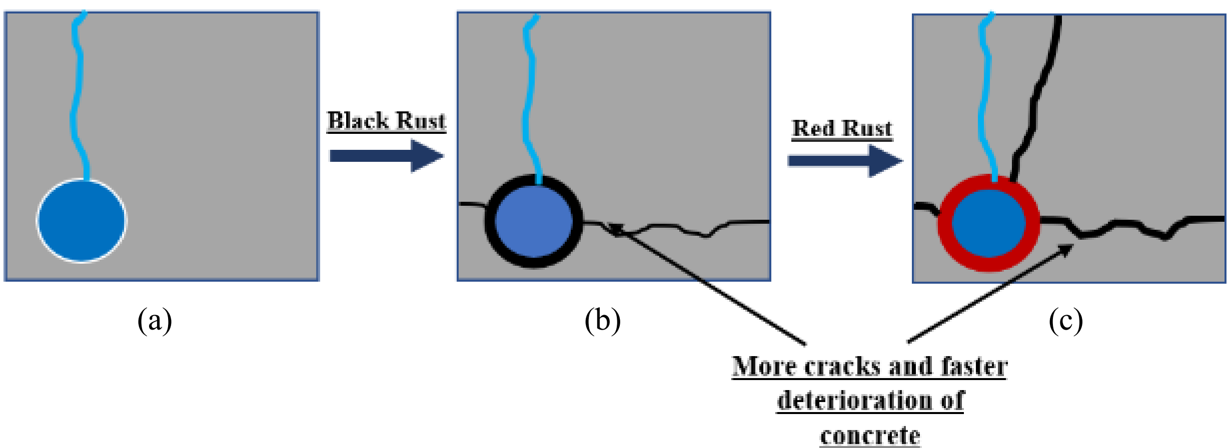


Figure 1 shows the stages of concrete deterioration due to corrosion from external chemicals penetrating through cracks. (a) External chemicals reaching the rebar through crack (b) black rust forms causing additional cracks (c) red rust forms leading to increased cracks and concrete deterioration.

To reduce the deterioration of reinforced concrete, different products such as epoxy, silane, or methyl methacrylate are added to the cracks to seal them. Currently, there is not much guidance on the performance of these products and the size of the crack that each product should be used to seal. This is investigated with this research.

Objectives of the research

- Quantify the relationship between crack size and the penetration depth of the silane products for cracks.
- Quantify the relationship between crack size and the performance of repair materials in preventing outside chemicals from penetrating.

2.0 EXPERIMENTAL Methods

2.1 Materials & Mixture design

A total of 124 samples were prepared with a typical mixture design used in concrete bridge decks as shown in Table 1. An ASTM C 618 Class C Fly ash was used at a 20% replacement [4]. The Portland cement was a Type I ASTM C150 and both the oxide analysis and the Bogue calculations for the cement used are shown in Table 2 [5]. The water-to-cementitious ratio (w/cm) was 0.45. The fine aggregate meets the fine aggregate standard for ASTM C33 and the coarse aggregate meets the #57 coarse aggregate standard for ASTM C33 [6]. No admixtures or other additives were used in the mixtures to minimize variables.

Table 1. Mixture Design

Cement lbs./yd^3	Fly Ash lbs./yd^3	Coarse Agg. lbs./yd^3	Fine Agg. lbs./yd^3	Water lbs./yd^3
488	122	1835	1195	275

Table 2. Oxide Analysis for Type I Portland cement and Class C fly ash

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	P_2O_5	C_3S	C_2S	C3A	C_4AF
Cement (%)	21.1	4.7	2.6	62.1	2.4	3.2	0.2	0.3	-	48	24	8.1	7.9
Fly Ash (%)	25.3	19	5.2	33	7.8	2.6	3.4	0.6	1.9	-	-	-	-

2.2 Mixing & Sample Preparation

Aggregates were collected from outside storage piles and brought into a temperature-controlled room at 73°F for at least 24 hours before mixing. Aggregates were placed in the mixer and spun, and a representative sample was taken for a moisture correction. At the time of mixing, all aggregate was loaded into the mixer along with approximately two-thirds of the mixing water. This combination was mixed for three minutes to allow the aggregates to approach the saturated surface dry (SSD) condition. Next, the cement, fly ash, and the remaining water were added and mixed for three minutes. After mixing, the mixture rested for three minutes while the inside of the mixing drum was scraped. After the resting period, mixing is continued for 2-3 more minutes.

2.3 Split Beam Test

2.3.1 Sample Preparation

The Split Beam test uses 6” x 6“ x 20” molds; however, smaller molds of 6” x 6” x 10” can also be used and similar results are obtained. The Split Beam test molds have a #3 rebar placed in the middle and wedges that are cast perpendicular to the rebar at the top and bottom of the beam. These wedges and load platen are created to have the same geometry. An overview of this is shown in Figure 2. The wedges are made of two pieces of ¼” thick mild steel that make up a “V” shape. The wedge is split at the bottom of the V. This causes the wedge to spread once loaded with the platen. This will cause a crack at a known location. The wedges are held together by glue while casting the fresh concrete [2-3].

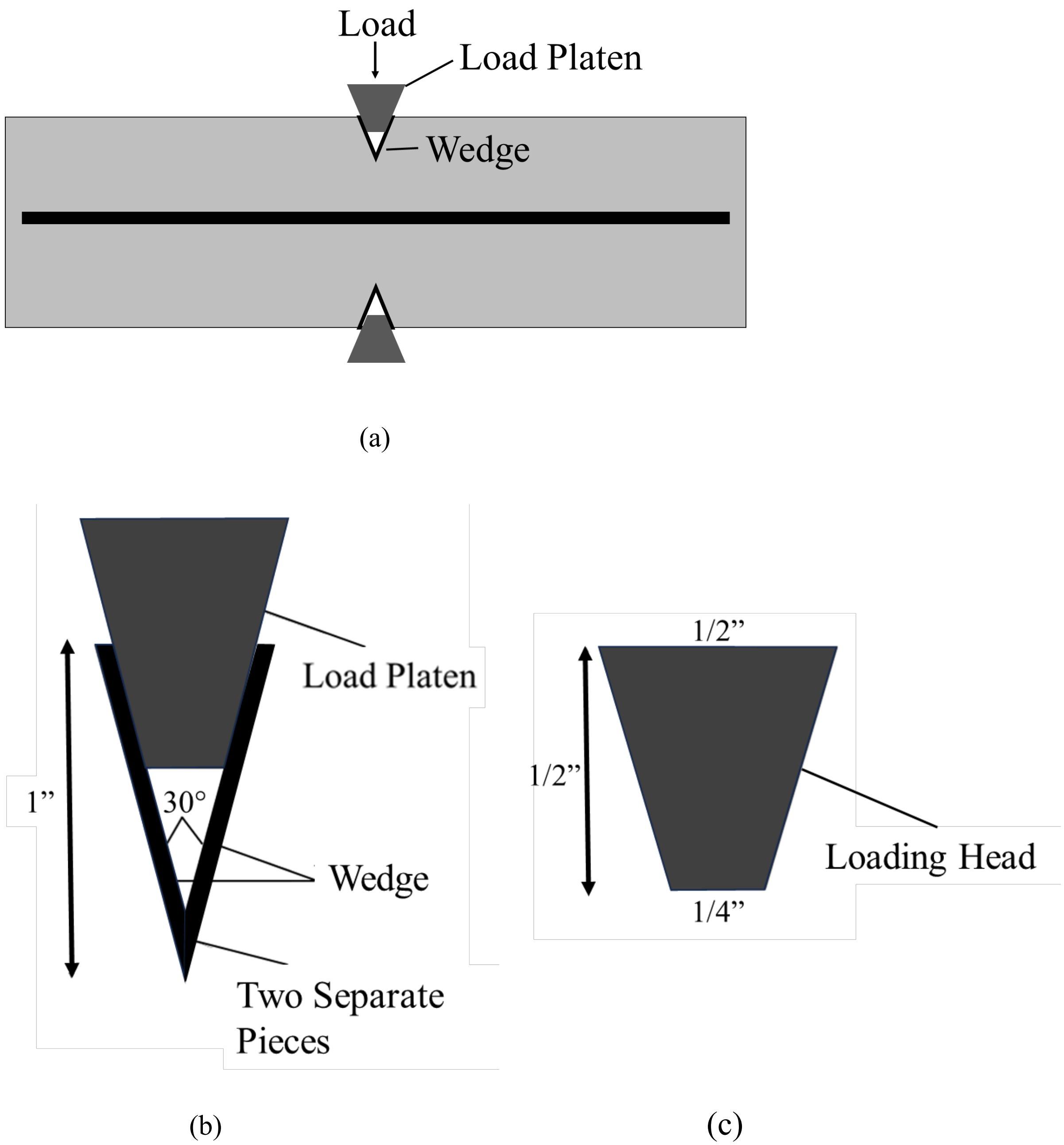
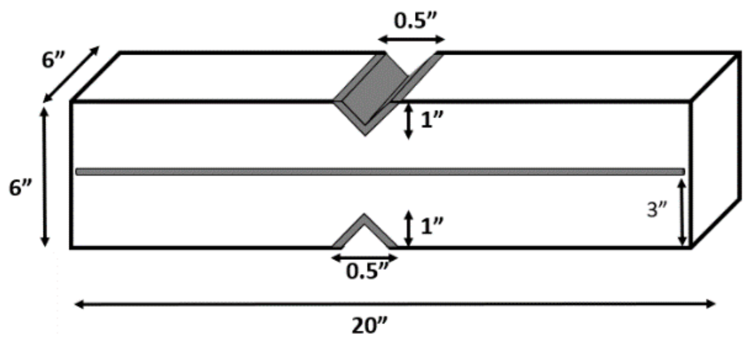
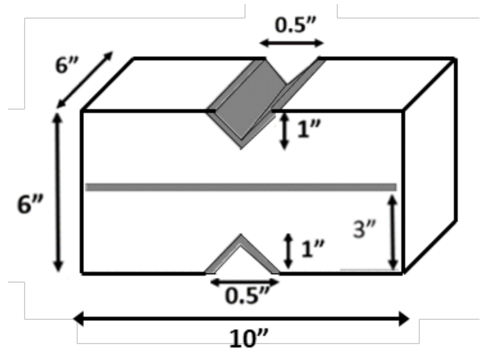


Figure 2 shows the schematic of the split beam and notch with (a) being an overall view (b) being a close-up image of the notch and (c) being a dimensioned image of the loading head.

The layout of the beam, notches, and rebar is shown in Figure 3. On each end, a 3” tall plastic chair is used to hold the rebar in place while the concrete is cast. The notches are glued together to keep them in place until loading. To ensure that the notches do not move from the middle of the beam, the notch is taped to the sides of the beam so no movement can happen.



(a)



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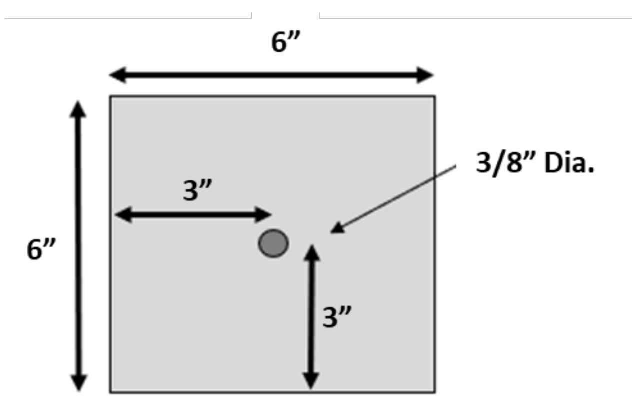


(c)

(d)

Figure 3 shows the schematic of the split beam showing the (a) front view for 6” x 6“ x 20” beams, (b) front view for 6” x 6” x 10” (c) side view, and (d) real image of the split beam.

2.3.2 Consolidation of sample beams

The beams were consolidated using an external vibrating table based on ASTM C192. The table ensures that neither the rebar nor the notches move during the consolidation process. The vibration duration was 5 +/- 1 second for each layer of the two layers and the vibrations per minute were 3600 vpm, per ASTM C192 [7]. The beams were then finished with a wood float until a flat surface was achieved, according to ASTM C192.

2.3.3 Curing conditions of sample beams

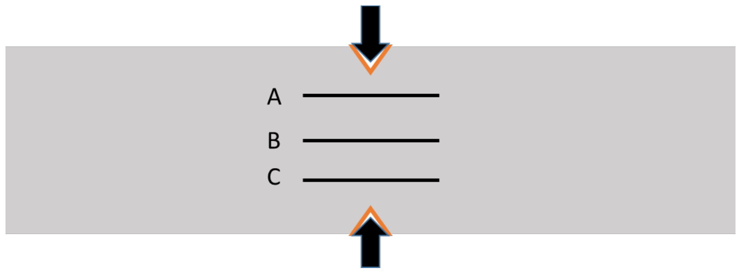
After the beams were cast and finished, they were covered with wet burlap and a tarp for 48 hours. The beams were then demolded and stored in an environmentally controlled chamber that was held at 73° F with a relative humidity of 100% for an additional 24 hours. All curing met the standards of ASTM C192. After a total of 72 hours of wet curing, the samples were placed in an environmentally controlled chamber that was held at 73° F with a relative humidity of 50% for at least 60 days before any product was added.

2.3.4 Placement of reinforcement steel

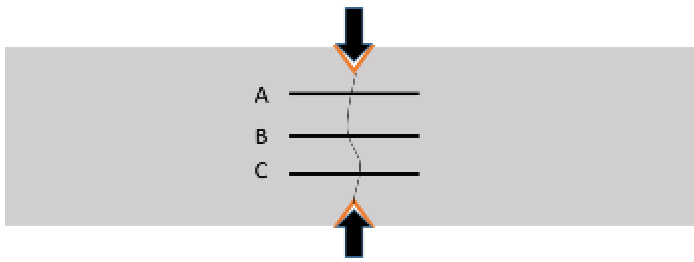
The rebar is included to hold the concrete together after a crack has formed. Tests were done using one #3 rebar, Grade 60 that is placed directly in the middle of the beam. This places the surface of the rebar approximately 1.8" from the face of the crack where the products are applied.

2.3.5 Loading of sample beams onto hydraulic supports

The main goal of the test is to induce predetermined cracks where the load on the beam is in tension. The notches at the top and bottom are intended to load the beam in a way to propagate a crack down the middle of the beam as shown in Figure 4. The beam is loaded at 1,500 lbs./min until a crack is formed and reaches the required crack size. More details about this procedure can be found in other publications [2-3].



(a)



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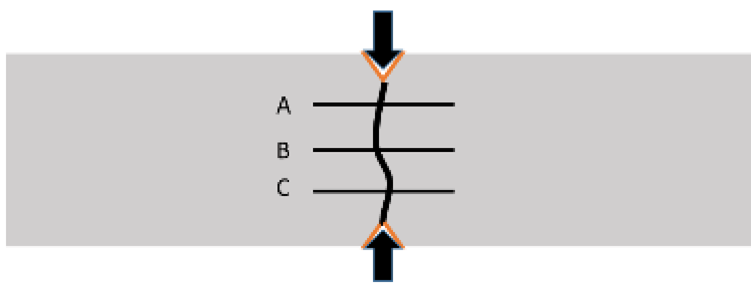


(c)

Figure 4 shows the schematic of the split beam loading steps (a) before cracking, (b) after some load is applied, and (c) after more load is applied.

2.4 Repair Materials: Silane and Corrosion Inhibitor, Epoxy, and Methyl Methacrylate

2.4.1 Types and Properties

Silane, epoxy, and methyl methacrylate products are tested for this research. Nine types of silane products are tested, Seven products with 90-100% silane content and two with 35-45% silane content. All silane products are surface applied liquids that use a functionalized organo-silane molecule to waterproof the concrete. Three of the silane products (Products 1, 2, and 5) contain a corrosion inhibitor to raise the chloride threshold level of the reinforcing steel. Five of these silane products (Products 2, 3, 4, 5, and 9) have a smaller molecular weight of 178.30 g/mol, while three silane products (Products 1, 6, and 7) have a larger molecular weight of 220.38 g/mol and Product 8 has the largest silane molecular weight of 276.49 g/mol. Silane is considered a vapor-permeable sealer, which means that it does not allow liquid to penetrate but allows vapor to leave the concrete. After silane is added, it penetrates the pores, the solvent present will evaporate, and the material that is left will react with the concrete, forming a hydrophobic layer. The initial reaction that silane undergoes is called hydrolysis. Slower hydrolysis of silane is expected to allow for deeper penetration into the concrete before the hydrolysis reaction concludes. This is anticipated to result in the formation of a thicker waterproof layer. Smaller silane molecules are also expected to hydrolyze faster compared to larger ones. For example, silanes with a molecular weight of 178.3 g/mole are expected to hydrolyze more rapidly than those with a molecular weight of 220.38 g/mole. As a result, the faster hydrolysis of the smaller silane molecules will limit their penetration depth. On the other hand, larger silane molecules are predicted to undergo slower hydrolysis. This enables them to penetrate deeper before they react with the concrete. This forms a thicker waterproofing layer in the concrete. A thicker waterproof layer is expected to have a longer service life in the concrete. The reported physical properties of the products are summarized in Table 3.

Three types of epoxies and one type of methyl methacrylate are tested. These products are considered impermeable sealers where they both penetrate the crack in the liquid state and then harden inside the crack preventing outside chemicals from penetrating. The reported physical properties of the epoxy products are summarized in Table 4, and the physical properties of the MMA product are summarized in Table 5.

Another type of silane has been tested, known as a bifunctional silane. This means that silane contains two parts: a part that is organic and an inorganic part. This allows it to couple with organic polymers such as epoxy resins and inorganic surfaces and create strong bonds with inorganic surfaces. In practice, this means that when this silane is mixed with epoxy resin it will make better bonds to the surface of the concrete. The bifunctional silane is recommended to replace 0.5% to 2.0% of the epoxy. In this report, the bifunctional silane is mixed with epoxy 1. The tested mix contained 98% epoxy 1 and 2% of the bifunctional silane. The properties of the bifunctional silane are summarized in Table 6.

Table 3: Properties of silane products used.

Product Number	1	2	3	4	5	6	7	8	9
Density (lb/gal)	7.36	7.68	7.68	7.68	7.68	7.34	7.34	7.3	7.7
VOC Content g/L	< 400	< 400	< 600	<350	-	<390	423	329	344
Silane Type	Isobutyl tri ethoxy silane	Isobutyl tri methoxy silane	Isobutyl tri methoxy silane	Isobutyl trimethoxy silane	Isobutyl tri methoxy silane	Isobutyl tri ethoxy silane	Isobutyl triethoxy silane	Octyl triethoxy silane	Isobutyl trimethoxy silane
Molecule Size (g/mol)	220.38	178.30	178.30	178.30	178.30	220.38	220.38	276.49	178.30
Other Products	-	Methanol	Methanol	Methanol	Methanol	-	Isopropanol, ethanol	Isopropanol, ethanol	Isopropanol, ethanol
Corrosion Inhibitor	Yes	Yes	No	No	Yes	No	No	No	No
*Active Ingredients	98%	90-98%	35-45%	90-98%	42%	90-100%	98%	98%	96%

*Active Ingredients: Percentage by weight of Silane within a product; Solids Content of Silane.

Table 4: Properties of epoxies used.

Product Properties	Epoxy 1	Epoxy 2	Epoxy 3
Density (lb/gal)	8.75	8.75	9.19
Viscosity (cps)	< 250	75-200	150
Linear Coefficient of Shrinkage	0.0021	0.0025	0.005
Percent Solids	100	100	94-97%
VOC Content g/L	0	0	8
Absorption	0.10%	0.68%	0.51%
Gel Time	20-30 min	16-34 min	40 min
Shore D Hardness	70-80	65-75	82

Table 5: Properties of methyl methacrylate used.

Product Properties	Methacrylate
Density (lb/gal)	7.51
Viscosity (cps)	< 25
Flash Point	> 180° F
Tack Free Time	< 400 minutes
Vapor Pressure, mm Hg	< 1 mm Hg
Volatile Content	< 30%

Table 6: Properties of the Bifunctional Silane

Product Name	Bifunctional Silane
Density (lb/gal)	8.93
Silane Type	γ-glycidoxypropyltrimethoxysilane
Solvent	Mixed with Resin
Components	1. Reactive Organic Group: glycidoxy 2. Inorganic Group: Trimethoxysilyl
Mix Proportions	98.0% to 99.5% Resin 0.5% to 2.0% Silane

2.4.2 Concrete Conditions before applying the products

For the repair materials to be effective, the concrete must be under the following conditions:

Concrete is stored in 50% relative humidity until mass change is less than 1%. It is common for samples to be tested after 60 d of drying before applying the product. The surface of the samples is cleaned of dirt and debris with air pressure.

2.4.3 Crack Sizes and Orientation

2.4.3.1 Importance of Crack Sizes and Orientation

Different crack sizes are used to test the penetration depth of each product. In addition to the crack size, the orientation of the crack plays an important role in the penetration of silane and corrosion inhibitors. Figure 5 shows different crack orientations that can be seen in a structure. For this report, a "flat crack" is a crack on a horizontal surface. A horizontal crack on a vertical will be known as a "horizontal crack" and a vertical crack on a vertical surface will be known as a "vertical crack". In this report, only flat crack test results are considered.

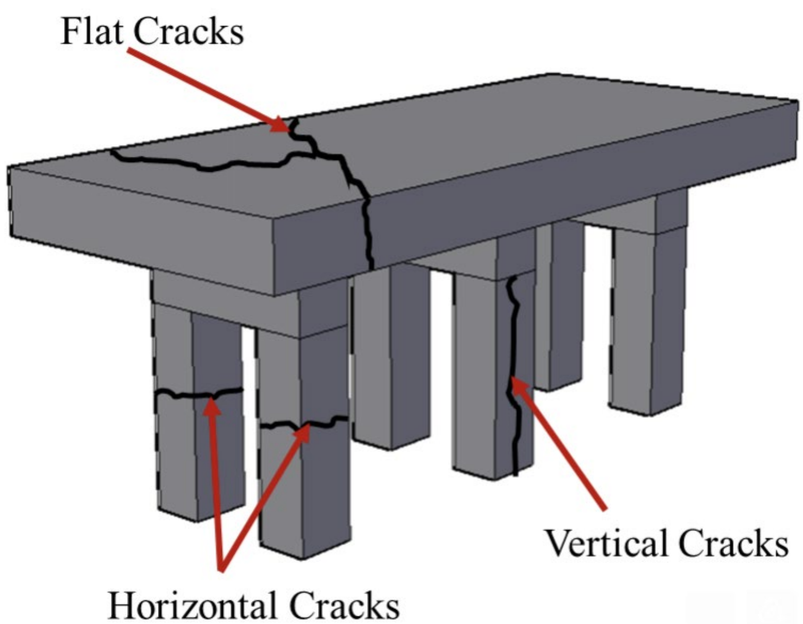


Figure 5: Crack Orientation

2.4.3.2 Adding Repair Materials to Flat Cracks

To investigate how the flat crack orientations impact performance, the split beam samples were loaded to form cracks. Next, the cracks were sealed with silicone except for the cracks in the top and bottom notch. Silicone was also added to the sides of the top-notch to create a dam on the surface of the sample. This is shown in Figure 6. The crack repair product is then applied to the notch. For samples of crack sizes less than 0.040”, a syringe is used to fill the notch with 20 ml of the repair product. The volume of material used is described in section 7.1 of the Appendix.

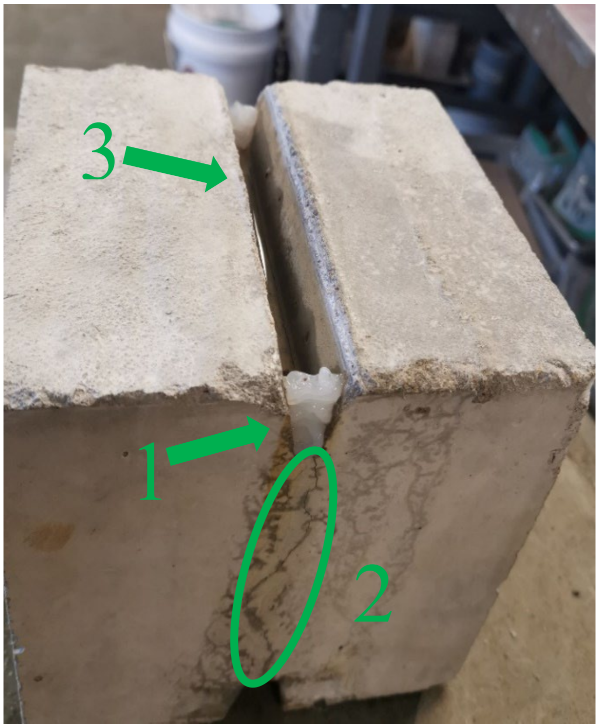


Figure 6: Product applied on flat crack

1. Silicone is applied to each end of the crack creating a dam.
2. Then the cracks along the sides of the samples are covered with the silicone. This creates a reservoir allowing the repair product to fill the notch and then penetrate into the crack.
3. 20 to 30 ml of product is added (Depending on the size of the crack)

2.4.4 Crack Sizes

2.4.4.1 Performance of Silane Products Test

To compare the performance of the nine silane products tested, a small crack of 0.002” was investigated. Crack size of 0.002” was used to investigate if the silane products would penetrate and waterproof the surface of the cracks in even the smallest crack sizes. The performance of this material in larger cracks will be investigated in the water penetration tests.

2.4.4.2 Water penetration test

Samples of crack sizes ranging between 0.005" and 0.060" were investigated to determine the performance of the repair materials (silane, epoxy, and methyl methacrylate) in preventing the outside chemicals from penetrating the crack.

2.4.5 Testing Procedure

2.4.5.1 Performance of Silane Products Test

To study the penetration of silane products, cuts are taken perpendicular to the crack, and water is added to the cut face to observe the areas where the silane is present. If the concrete is wetted by the water and becomes dark then this means the water has penetrated the concrete and there is no waterproofing silane present. If the concrete does not change color and the concrete stays light then this means the product has penetrated the concrete and waterproofed that region. This technique of using water to check for silane location has been validated by using XRF microscopy in previous publications to map the location of silane based products [8] [9].

The length of the crack is determined by taking digital pictures and manually tracing the length of the crack. The process of quantifying the percentage of the crack coated and quantifying how deep the silane penetrated the concrete is done through image processing techniques in Python. The image processing techniques detect the light regions and consider them as the waterproofing portion of the concrete. The percentage of the crack coated is determined by computing the ratio of the silane-covered crack length to the total crack length. As for how deep the silane penetrated the concrete, it is quantified by calculating the area of the waterproofing and then it is divided by the silane-covered crack length. The result is divided by 2 to calculate the waterproofing thickness on each side of the crack.

An overview of the cuts is shown in Figure 7. Cuts are taken along the rebar and two cuts are taken 1” from the side of the beam. This allowed the depth of penetration of the product to be investigated in three places and also to investigate the coating of the rebar.

The assessment of rebar coating is achieved by evaluating the proportion of samples featuring waterproof coating around the rebars, divided by the total number of samples employed.

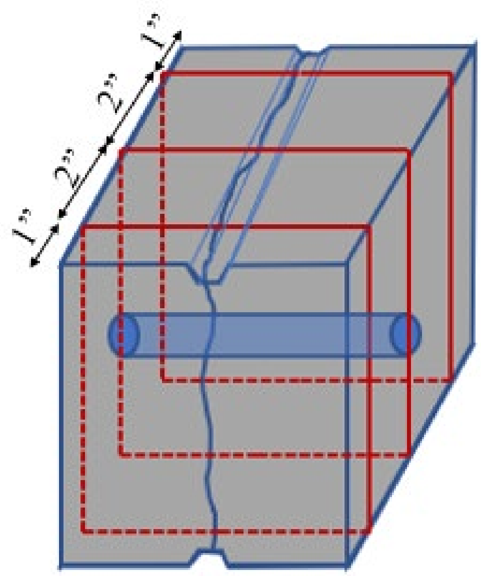
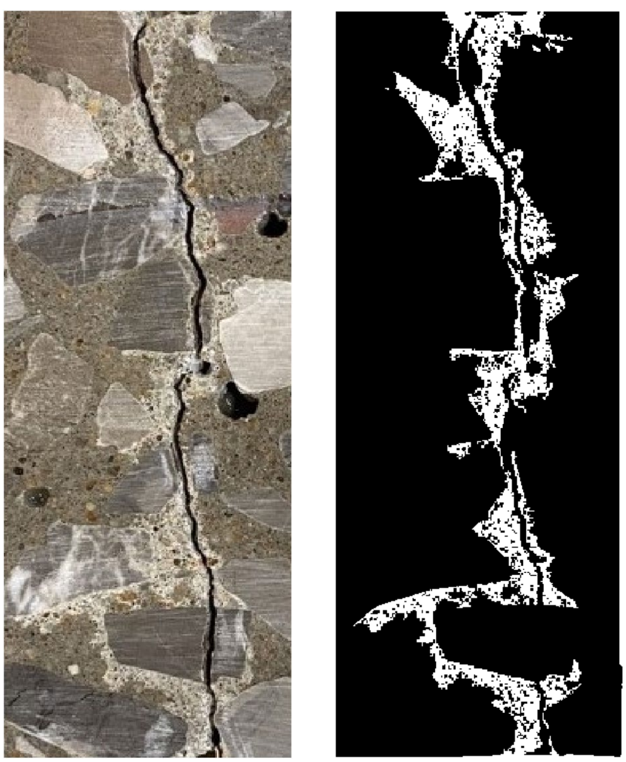


Figure 7: Cuts for flat cracks.

3.0 Results and Discussion

3.1 Typical Silane Product Coating and Penetration Results

For silane product 6, figure 8 shows a typical result from a sample with a crack of 0.002”. Figure 8a shows a cut of the sample that has been ponded in water. The waterproof part of the concrete repels water, while the non-waterproof section absorbs water, resulting in a darker appearance. Figure 8b displays the same image after undergoing image processing, highlighting only the waterproof regions. The highlighted areas shown are used to calculate how much of the crack is coated with silane and thickness of the waterproofing regions. This product penetrated 100% of the depth of the crack.



(a) (b)

Figure 8: Typical results of the silane products with 90-100% active ingredients and medium silane molecule size. (a) represents a sample after ponding it water. (b) shows the same sample after image processing to show the waterproofing regions around the crack.

For silane product 9, figure 9 shows a typical result from a sample with a crack of 0.002”. The white areas shown in the figure represent the waterproof layer. This product penetrated 63% of the depth of the crack.

(a) (b)

Figure 9: Typical results of the silane products with 90-100% active ingredients and small silane molecule size. (a) represents a sample after ponding it water. (b) shows the same sample after image processing to show the waterproofing regions around the crack.

For silane product 3, figure 10 shows a typical result from a sample with a crack of 0.002”. The white areas shown in the figure represent the waterproof layer. This product penetrated 35% of the depth of the crack.

(a) (b)

Figure 10: Typical results of Silane products with 35-45% of active ingredients (Silane only). (a) represents a sample after ponding it water. (b) shows the same sample after image processing to show the waterproofing regions around the crack.

Table 7 and Figures 11 and 12 show all the results of products 1 through 9 for small crack sizes (0.002" in size). For the products with 90-100% active ingredients (products 1, 2, 4, 6, 7, 8, 9), a higher percentage of the crack was coated with silane compared to the products with 35-45% active ingredients (products 3 and 5) which shows that silane with higher active ingredients can coat more of the crack. The products with molecular formulas of 220.38 g/mol and 276.49 g/mol (products 1, 6, 7, and 8) coated around 100% of the crack which is higher than that of silanes with high active ingredients and a molecular formula of 178.30 g/mol (products 2, 4, and 9) where the coverage of coating ranged between 65% and 80%. This shows that larger silane molecules do a better job of coating the cracks.

Moreover, products 1, 7, and 8 (larger silane molecules of 220.38 g/mol and 276.49 g/mol) penetrated deeper into the concrete and provided a larger depth of waterproofing.

Product 6 which is a silane with a molecular formula of 220.38 g/mol also penetrated deep into the concrete and provided a large depth of waterproofing, but not as much as products 1, 7, and 8. Products 3, 4, 5, and 9 (silanes with a molecular formula of 178.30 g/mol) exhibited less penetration into the concrete. Product 2, also featuring a smaller silane molecule of 178.30 g/mol, outperformed Products 3, 4, 5, and 9. This improved performance may be because it contains a corrosion inhibitor. This shows that silanes with larger molecular formulas can provide deeper waterproofing than the ones with smaller molecular formulas.

Most of the products investigated provided a satisfactory coating around the rebar. The only products that did not do as well are products 2 and 5, and this can be attributed to the high standard deviation in these two products, indicating inconsistency in performance. All the samples from products with molecular formulas of 220.38 and 276.49 showed coating around the rebar.

Table 7: Results of all nine silane products with a crack size of 0.002" after 7 days of curing the silane.

Product Number	Active Ingredients	Silane Molecule Size (g/mol)	Average Crack Coated	Standard Deviation Crack Coated	Average Thickness (in)	Std Deviation Average Thickness	Rebar Coating
1	98%	220.38	99%	2%	0.163	0.057	100%
2	90-98%	178.30	80%	17%	0.081	0.022	75%
3	35-45%	178.30	46%	10%	0.038	0.005	100%
4	90-98%	178.30	66%	8%	0.038	0.012	100%
5	42%	178.30	53%	21%	0.048	0.021	67%
6	90-100%	220.38	100%	0%	0.083	0.012	100%
7	98%	220.38	99%	2%	0.172	0.049	100%
8	98%	276.49	100%	0%	0.149	0.044	100%
9	96%	178.30	65%	17%	0.029	0.027	100%

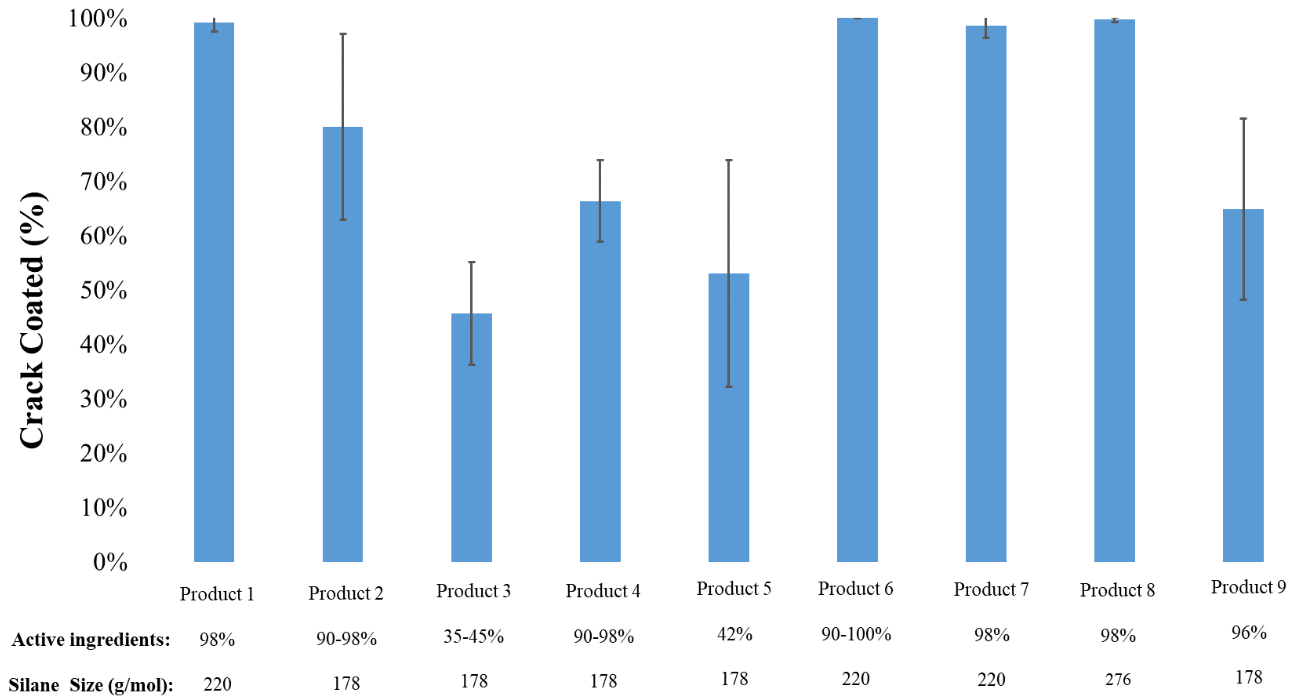


Figure 11: Performance of the silane products in coating the crack.

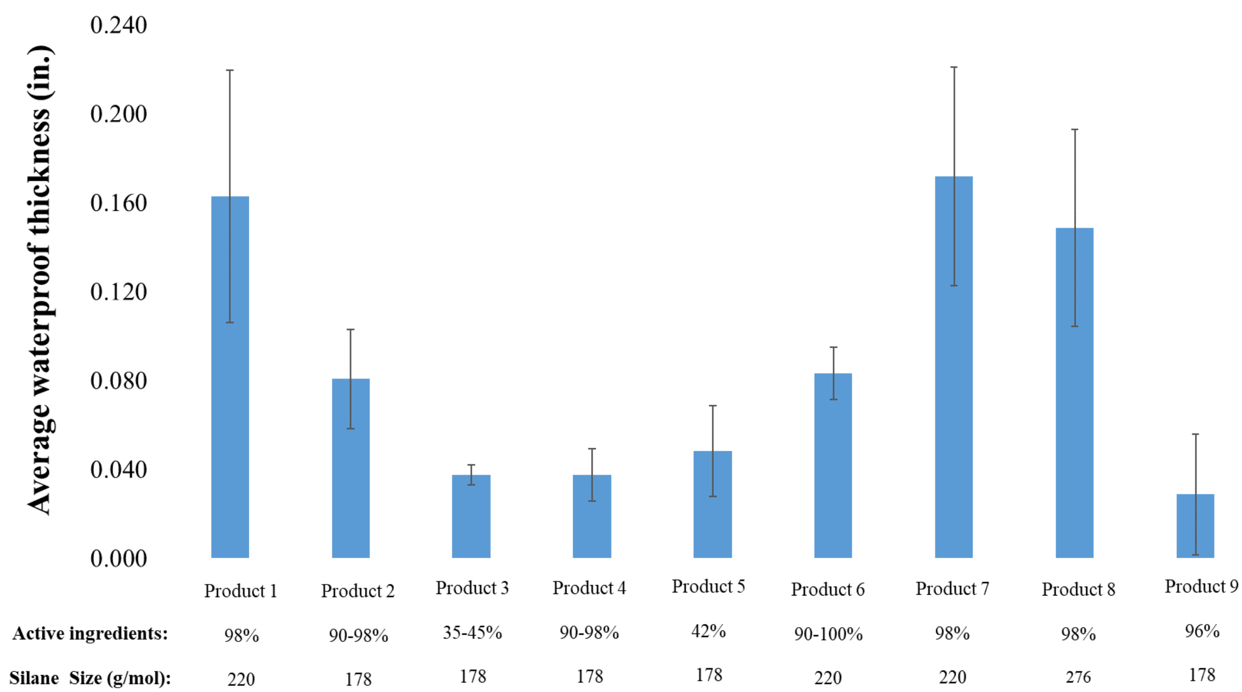


Figure 12: Penetration depth of silane into the concrete surrounding the crack.

3.2 Summary of Product Performance

Products 1, 7, and 8 showed the thickest layer of waterproofing and also the most penetration along the crack. Product 6 also showed good penetration along the crack but not as much depth of penetration. All of these silanes coated the reinforcing bar when they penetrated the crack.

The one thing in common about these products is that they have a molecular weight > 220.38 g/mol. This means that these materials seem to have superior performance. Further, product 1 seems to be the best if it is desirable to use a corrosion inhibitor at the level of the reinforcing bar. Products 7 and 8 seem to show superior performance to product 6. Product 8 uses the largest molecular weight at 276.49 g/mol. This is likely why it has superior performance. Products 6 and 7 have similar molecular weights so the difference in performance may be the carrier or the material that the silane is dissolved within. For example, product 7 seems to be dissolved in isopropanol and ethanol while product 6 does not. This seems to raise the VOC of the product slightly from 390 to 423. The isopropanol and ethanol carriers seem to improve the performance of the silane.

This work shows that certain silane products have superior performance over others and that there is a difference in performance based on the silane molecule size. Based on the investigation of crack penetration, ability to coat rebar, and penetrate the concrete it is recommended to use either isobutyl tri ethoxy silane (molecular weight 220.38 g/mol) or octyl triehoxy silane (molecular weight 276.49 g/mol) that has a percentage by weight of silane or solids content of silane > 90%. These materials should also be dissolved in isopropanol or ethanol. This language could be used within a specification for silane usage with or without a corrosion inhibitor. Another simple way to specify these products is that all of them have a of < 7.40 lb/gal. One needs to be careful only approving these materials based on the density as other materials could be added to the silane that may change the density but not improve the performance.

It is also possible to create a performance based testing approach similar to the tests outlined in this report. For these tests, it would be important that the silane penetrates 100% of the depth of the crack, penetrates around the rebar, and also forms a coating on the surface of the concrete that is on average $\geq$ 0.075". Tests should be done with replicate silanes used in this study to compare performance to the new material.

3.3 Water Penetration for Repair Materials

This section investigates the performance of water penetration within cracked concrete with different repair products. To study the effectiveness of the repair materials in preventing outside chemicals from penetrating the cracks, 20 grams of water is added to fill the notch. This volume of water was chosen as the water will fill the notch without causing it to overflow. Next, the duration taken for the water to penetrate the crack is observed and this is used to evaluate the performance of the repair product used. This means that products that can keep the water out for longer show better performance than those that keep the water out for shorter times.

The samples are placed in a sealed hood to prevent the water from evaporating, and a camera is used to record the time at which all the water penetrates. This allowed the performance of the repair materials to be investigated for their ability to repair cracks of different sizes.

The same split beam samples and repair product application were used as described previously and as shown in Figure 6. The crack repair product was used to fill the notch, and the repair material penetrated only through gravity. For samples of crack sizes less than 0.040", a syringe is used to fill the notch with 20 ml of the repair product. For samples with cracks between 0.040" and 0.050”, 25 ml is used because the volume of the crack is bigger. For samples with cracks between 0.050” and 0.060”, 30 ml is used. More details can be found in section 7.1 in the Appendix.

The silane chosen for the water penetration tests is product 6. It was chosen because it performed well in covering most of the cracks and penetrating deep into the concrete. It is also consistent, which decreases the amount of variables when doing the water penetration test for silane.

3.4 Water Penetration Test Method

To study the effectiveness of the repair materials in preventing outside chemicals from penetrating the cracks, 20 grams of water is added to fill the notch. This water volume was chosen as it will fill the notch without causing it to overflow. Next, the duration taken for the water to penetrate the crack is observed and this is used to evaluate the performance of the repair product used. This means that products that can keep the water out for longer show better performance than those that keep the water out for shorter times.

The samples are placed in a sealed hood to prevent the water from evaporating and a camera is used to record the time at which all the water penetrated. This allowed the performance of the repair materials to be investigated for their ability to repair cracks of different sizes. In the water penetration test conducted on silane product 6, Figure 13 displays the outcomes obtained from a sample featuring a crack size of 0.008". This specific sample, treated with silane product 6, demonstrates the effective prevention of water penetration into the 0.008" crack for 67 hours.

(a) At t = 0 hours (b) At t = 48 hours (c) At t = 67 hours

Figure 13: Water Penetration Test Illustration. (a) Presents an image captured immediately after introducing water into the notch. (b) An image taken 48 hours later, shows that water is still present. (c) Shows where water is no longer present within the notch.

3.5 Determining the Critical Time for Water Penetration

This work shows that repair products can delay the penetration of outside water but they do not keep the water out permanently. This means that a critical time needs to be found where if water does not penetrate the cracked concrete over this time then it is deemed acceptable. The critical time that a product must perform in a crack is a function of the weather at the repair the expected amount of rain and the duration of the rain.

According to the US National Centers for Environmental Information, between 1991 to 2020 the average total yearly precipitation for Oklahoma is around 36.4 inches with an average of 83 days of rain every year [10]. According to the Manual of Surface Weather Observations (MANOBS), a moderate rain intensity ranges between 0.10"/h and 0.30"/h [11]. Assuming a moderate rain intensity of 0.20"/hour, the average duration of precipitation on a rainy day can be calculated as an example:

Equation 1:

Average duration of precipitation/rainy day $= \frac{36.4\ inches}{83\ rainy\ days \times 0.20\ inches/hour} = 2.2\ \frac{hrs}{rainy\ day}$

This would provide an estimate of the average length of time of a rain event. Instead of designing for the average, the 95th percentile value was calculated by examining the duration of rainfall for all rainy days since 1996. For 95% of these days, the rainfall lasted < 8.9 hours. To account for the time for the water to drain or evaporate a time of 10 h was used as the critical time that the repair material would have to resist water penetration.

3.6 Results

When no repair materials are added, the water added penetrates quickly through the crack. Table 8 shows that even when the crack size is as small as 0.002", the water will penetrate through the crack in less than 30 minutes. As for slightly larger cracks, it would take only a few minutes for all the water to penetrate.

Table 8: Results of the water penetration into the cracks without any repair materials added compared to the size of the crack.

Average Crack Size	Time to Penetrate (mins)
0.001-0.004	10-30
0.005-0.009	5 -10

Average Crack Size	Time to Penetrate (mins)
0.010-0.014	1-5
> 0.015	< 1

Figure 14 shows the performance of Epoxy 1 in preventing water from penetrating cracks of different sizes. Each data point on the graph corresponds to a sample with a specific crack size and reflects the duration it took for the water to penetrate through that crack size. The trendline displayed represents a curve fitted to the data points within the figure. A dotted horizontal line at 10 hours denotes the critical time for Oklahoma, as detailed in Section 3.4. The point where the fitted curve intersects with the critical time for Oklahoma signifies the crack size at which Epoxy 1 stops being effective.

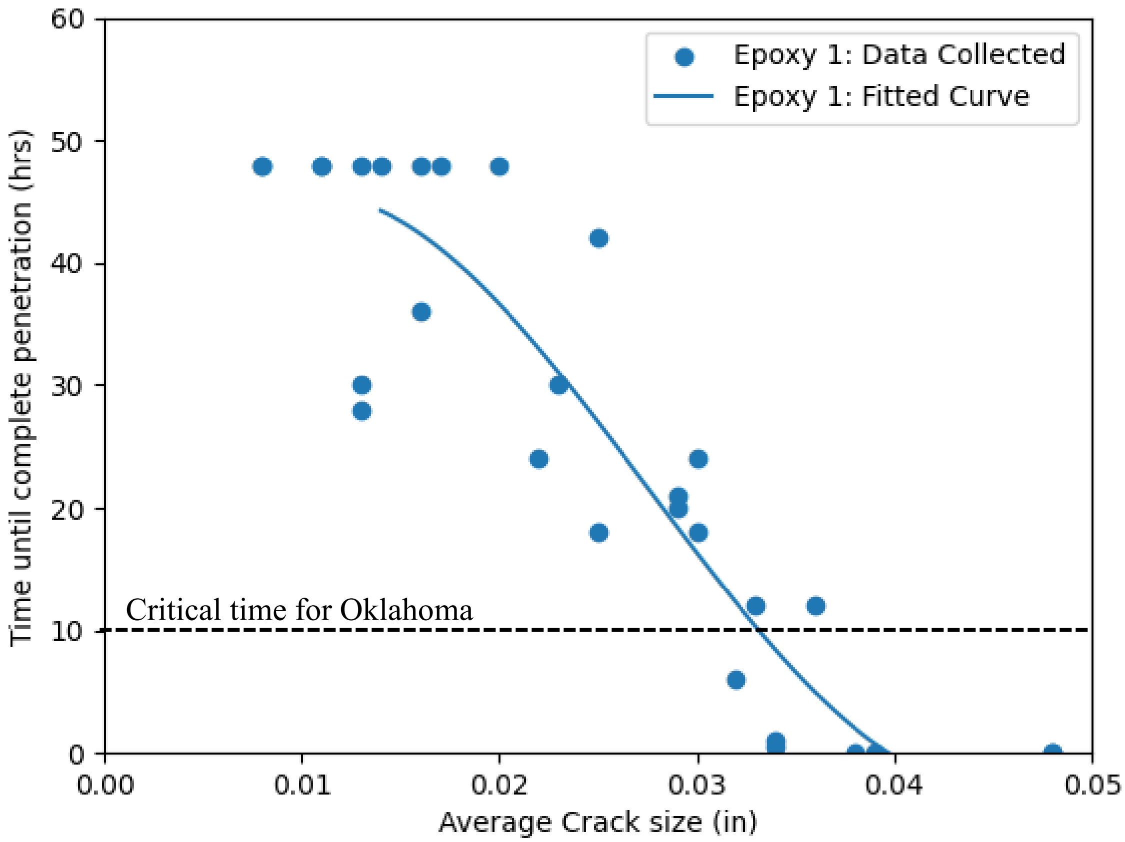


Figure 14: Performance of Epoxy 1 in preventing water from penetrating cracks of different sizes.

Figure 15 shows the fitted trend lines for the different products. The complete data sets for each product are included in the appendix. A total of 171 tests were done to create Figure 15. Each repair material was matched with the best-fit equation or function for the measured data points. The selection of the best-fit equation was based on the data's characteristics. For silane product 6, a step function was used due to the clear transition from being completely effective to becoming completely ineffective at a specific crack size. As for the other curves, they were chosen to identify the equation with the highest r^2 value.

The results show that different products perform better at different crack sizes. For example, the silane product investigated was only able to seal narrow cracks, while methacrylates can protect larger cracks, and epoxies even larger cracks. In the case of epoxy, epoxies 1 and 2 demonstrated comparable performance where the critical crack size at which they were able to prevent water from penetrating for more than 10 hours is around 0.033”, whereas epoxy 3 was around 0.030”. Moreover, the samples where silane was added before epoxy 1 showed slightly better performance compared to epoxy 1 used alone and this material did better than other epoxies at crack sizes < 0.035”. The differences in the performance of the epoxies are small and so in practice it is recommended that an epoxy can prevent water from penetrating cracks that are 0.030” for Oklahoma. Although epoxies can be observed to fill larger cracks than this, it appears that these cracks are not filled sufficiently. This means there seems to be some debonding from the walls of the concrete by the epoxy as it shrinks.

The best results of the materials investigated were with a mixture of bifunctional silane and epoxy 1. The combination of the materials seems to create a better bond between the epoxy and the concrete surface. This helps the material sufficiently seal larger cracks in the concrete.

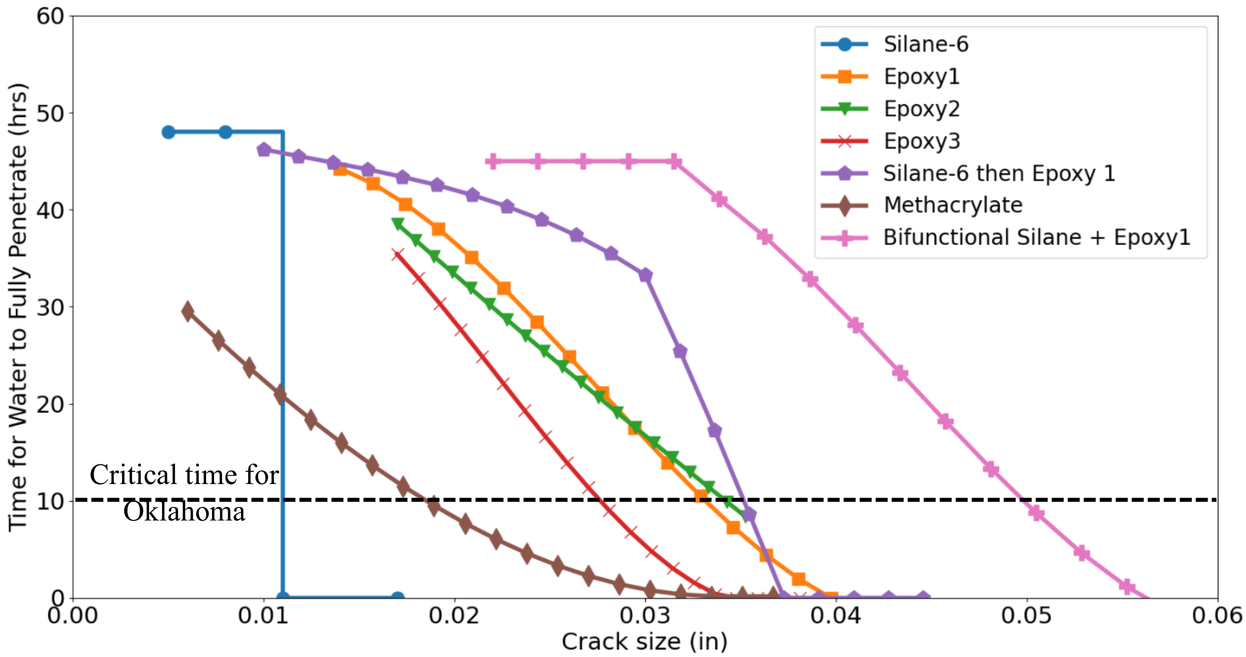


Figure 15: Performance of repair materials in preventing water from penetrating the cracks compared to the crack size.

If a critical time of 10 h is used then this provides a maximum crack size that a repair material can be used where the repair material is expected to keep moisture out of the crack. This point can be found where the dashed line intersects the curve for the different repair products. The critical crack size for each repair product is determined and shown in Table 9. If a crack is smaller than the critical size in the table then that repair product is acceptable. If the crack size is larger then a different repair product is needed. For example, if a crack of 0.025" needs to be repaired, then products such as silane 6 and MMA would not be effective, whereas the other products mentioned in the table would be effective as they have larger critical crack sizes.

Table 9: Critical Crack Size at which the repair materials can prevent water penetration for 10 h. A single value for epoxy has been used to simplify the implementation in practice.

Repair Material	Critical Crack Size (in)
Silane 6	≤ 0.011
MMA	≤ 0.019
Epoxy	≤ 0.030
Silane 6 then Epoxy 1	≤ 0.036
Bifunctional Silane Mixed with Epoxy 1	≤ 0.050

3.7 Recommendations

Based on this work it is recommended to survey a bridge deck surface and determine the largest crack sizes. Based on the size of these cracks one can use Table 9 to determine which product should be used. As long as the crack size is smaller than the limit in Table 9 then it should show satisfactory performance.

The reader should realize that these recommendations are for sealing cracks and not for all maintenance purposes on a bridge. The use of silane sealers are powerful tools to create a hydrophobic layer on the surface of the concrete and reduce the penetration of outside chemicals. Past research has shown that silanes last for at least 12 y in Oklahoma bridge decks if they are applied at least 1/8" in thickness [9]. The use of silanes will help protect the overall surface of the bridge deck and these materials can be reapplied sufficiently as long as a non water based carrier is used to apply the silane.

4.0 Summary

This work completed a systematic study to determine the performance of different silane sealers and how these materials perform at penetrating cracks, waterproofing the sides of the crack, and coating the surface of rebars intersected by the cracks. Further, these same techniques were used to compare the performance of several different repair products and their ability to keep moisture out of concrete for an extended period. Both these findings provide key data that has not existed in the literature previously with a large group of testing in a practical manner. This work goes on to make several recommendations for implementation and possible changes to existing Oklahoma DOT specifications.

The Major observations in this work are:

1. Silane with > 90% active ingredients performs better than silane with 35-45% active ingredients.
2. Larger silane molecules (molecular weight ≥ 220.38 g/mol) coat a larger percentage of a crack and penetrate deeper into the concrete over smaller silane molecules. This is likely caused by differences in the rate of hydrolysis of the larger silane molecules.
3. A critical period of 10h is found to protect water from penetrating in 95% of all rain events in Oklahoma.
4. Silane can prevent water from penetrating a crack opening of ≤ 0.011" for 10h.
5. Methyl methacrylate can prevent water from penetrating a crack opening of ≤ 0.019" for 10h.
6. Epoxies can prevent water from penetrating a crack opening of ≤ 0.030" for 10h.

7. The bifunctional silane mixed with epoxy 1 showed the best performance of all of the repair products and it can prevent water from penetrating a crack opening of $\leq$ 0.050” for 10h. This is attributed to a better bond between the epoxy and the concrete.

<u>4.1 Future Work</u>

This work shows that the repair material products can protect against the penetration of outside chemicals until they reach a critical crack size. However, only one type of Methyl Methacrylate was investigated. So, the findings from this work would be improved by investigating more of these materials. It would also be valuable to test more samples that are treated with silane followed by epoxy, and also silane followed by bifunctional silane and epoxy. It would also be a good idea to test samples that are treated with silane followed by Methyl Methacrylate. These are all areas of future work.

5.0 Recommendations

5.1 Silane Specification Recommendations

Based on the investigation of crack penetration, ability to coat rebar, and penetrate the concrete it is recommended to use either isobutyl triethoxy silane (molecular weight 220.38 g/mol) or octyl triehoxy silane (molecular weight 276.49 g/mol) that has a percentage by weight of silane with a solids content of silane $\geq$ 90%. Another simple way to observe these products is that they have a density of < 7.40 lb/gal. A prescriptive specification for these materials is given below.

Another approach is to use performance based testing similar to the tests outlined in this report. For these tests, it is recommended that the silane penetrates > 95% of the depth of the crack, penetrates around the rebar, and also forms a coating on the surface of the concrete that is on average $\geq$ 0.075”.

5.2 Prescriptive specification language for silane usage:

All silanes used will have a percentage by weight of silane or solids content of silane $\geq$ 90%. Further, these silanes will be made of either isobutyl triethoxy silane or octyl triethoxy silane. A blend of these materials is also satisfactory. These silanes will use a non water based carrier such as isopropanol, methanol, or ethanol. The density of the silane will also be < 7.40 lb/gal. Plan sets may require the use of silane and corrosion inhibitors.

5.3 Performance Specification for Silane usage:

The silane must be shown to penetrate > 95% of the depth of a 0.002" crack and coat the rebar in split beam testing. Further, the silane penetration thickness must be > 0.075". The testing shall be complete as per ODOT report 2287.

5.4 Crack Sealing Recommendations

It is recommended to survey a bridge deck surface and determine the largest crack sizes. Based on the size of these cracks one can use Table 9 to determine which product should be used. As long as the crack size is smaller than the limit in Table 9 then the repair product should show satisfactory performance to prevent water penetration for 10h. Table 9 is replicated below for the ease of the reader.

Table 9: Critical Crack Size at which the repair materials can prevent water penetration for 10 h.

Repair Material	Critical Crack Size (in)
Silane 6	≤ 0.011
MMA	≤ 0.019
Epoxy	≤ 0.030
Silane 6 then Epoxy 1	≤ 0.036

Repair Material	Critical Crack Size (in)
Bifunctional Silane Mixed with Epoxy 1	≤ 0.050

The reader should realize that these recommendations are for sealing cracks and that they may not meet all maintenance needs. The use of silane sealers are powerful tools to create a hydrophobic layer on the surface of the concrete and reduce the penetration of outside chemicals. It is recommended to use silanes in combination with these other products to improve the service life of bridges. Further, silanes can be reapplied after the initial service life of the silane. Past research has shown that silanes last for at least 12y in Oklahoma bridge decks if they are applied at least 1/8” in thickness [9].

6.0 REFERENCES

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7.0 APPENDIX

7.1 Amount of Repair Materials Added

To determine the appropriate quantity of repair material required to repair a crack the volume of the crack must be calculated and enough repair material is needed to exceed this volume. For this work, a volume of 20% more material was used. Calculations are shown for cracks < 0.040", between 0.040" and 0.050", and between 0.050" and 0.060". The detailed calculations are presented below.

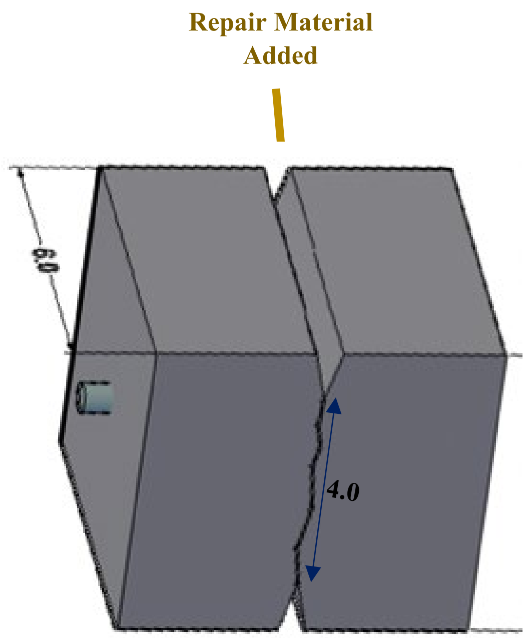

Figure A1: Amount of Repair Material Added

Calculate the Maximum Volume of the Crack

Volume = H x W x L

Crack Width ranges:

Crack width $\leq$ 0.040": Volume added = 4*0.040*6 + 20% extra = 1.152 in^3 = 18.9 ml

Thus 20 ml is added for Crack width ≤ 0.040”

0.040” < Crack width ≤ 0.050”: Volume added = 4*0.050*6 + 20% extra = 1.44 in^3 = 23.6 ml

Thus 25 ml is added for 0.040” to 0.050” crack width

0.050” < Crack width ≤ 0.060”: Volume added = 4*0.060*6 + 20% extra = 1.728 in^3 = 28.3 ml

Thus 30 ml is added for 0.050” to 0.060” crack width