THE EFFECT OF CRACK MOTION DURING EPOXY CRACK INJECTION AND CURING

Final Report

SPR 611

THE EFFECT OF CRACK MOTION DURING EPOXY CRACK INJECTION AND CURING

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by

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16. Abstract

One strategy to regain structural integrity of cracked reinforced concrete bridge deck girders is to inject the cracks with epoxy. Many bridge owners allow all traffic to use the bridge during injection and curing, while other bridge owners restrict traffic to produce a hold time in which cracks do not open and close. This research study used a laboratory set up to determine the effect of temperature and hold time on epoxy undergoing curing. The comparative measure was the tensile strength of the epoxy after curing. The results showed that traffic should be restricted to stop the crack motion during injection and until the epoxy sets. After the epoxy has set, crack motion while the epoxy undergoes full cure degrades the tensile strength of the epoxy, but not to levels that would affect the structural integrity of the beam.

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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	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	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	Mg
		PRESSURE		
psi	pounds per square inch	.0068948	megapascals	MPa
		TEMPERATURE (exact)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C

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	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
m^2	meters squared	1.196	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		PRESSURE		
MPa	megapascals	145.038	pounds per square inch	psi
		TEMPERATURE (exact)		
°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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THE EFFECT OF CRACK MOTION DURING EPOXY CRACK INJECTION AND CURING

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1.0 INTRODUCTION

1.1 BACKGROUND

Bridges with shear cracking and girder-deck separation cracking require injecting the cracks with epoxy to regain concrete capacity. Generally, the traffic on the bridge is not restricted during injection; consequently, some injected cracks are opening and closing while the epoxy cures. It is unknown how cyclic straining during curing affects the performance of the cured epoxy and the bulk integrity of the concrete.

Crack injection is a costly operation, but it is commonly used as a repair method itself, or as preparation for other strengthening schemes. However, this type of repair assumes that the injected cracks have restored the bulk concrete capacity of the structure. If the strength of the epoxy, or bond, is compromised significantly, the concrete strength will not be restored to the expected levels.

The objective of this research was to determine whether crack movement due to traffic during epoxy curing, degrades the ability to restore concrete strength in cases where cracks are injected with epoxy.

1.2 LITERATURE REVIEW

Tests by Macdonald (*1981*) on steel lap joints, joined together with epoxy, showed an average reduction of shear strength of 16% for one type of epoxy and no strength reduction for a second type of epoxy due to movement during curing. Similar studies of lap joints by Barnes and Mays (*2001*) reported that strength reduction increases as the extent of movement during curing increases. In the same study, Barnes and Mays reported that for large scale reinforced concrete beam specimens with external reinforcement, failures in the concrete masked any effect of vibration during curing of the adhesive. Similarly, Swamy and Jones (*1980*) showed no deleterious effects on load capacity for reinforced concrete beams externally reinforced and subjected to vibration during curing. The beam failures were all by concrete crushing, which suggests any deficiency in the epoxy adhesive was masked by the properties of the concrete.

2.0 PROCEDURE

2.1 STATE SURVEY

A short questionnaire was sent to state transportation agencies to determine the level of understanding of curing and injection effects of epoxies. The questions and a summary of the responses are shown in Appendix A. The results of the literature search and the questionnaire did not provide a thorough understanding of the live load effects on curing and of crack injection fill. Consequently, a series of experiments were conducted to explicitly address the project objectives.

2.2 CURING EXPERIMENTS

A design of experiment (DOE) was conducted in the laboratory to investigate the effect of crack motion during curing on the bond strength of epoxy. Temperature and hold time before applying crack motion were the variables. The hold time represented the situation in which traffic is not allowed on the structure. The simulated crack width was kept constant for all tests. A set of screening tests was conducted to select one of the crack injection epoxies on Oregon DOT's qualified products list. The selected epoxy was used for all of the remaining tests in the DOE.

Each test used the assembly illustrated in Figure 2.1 for cyclically loading the epoxy. The ratio of the steel fixture's reduced section, to the platen section, provided an effective elastic modulus for the fixture, similar to that of concrete based on $E_{con}=4x10^6$ psi and $E_{steel}=30x10^6$ psi. The length of the fixture between the machine's grips represented a situation on a bridge with cracks separated by approximately three feet. A second fixture, with removable platens, was also used during each test to establish the static condition bond strength.

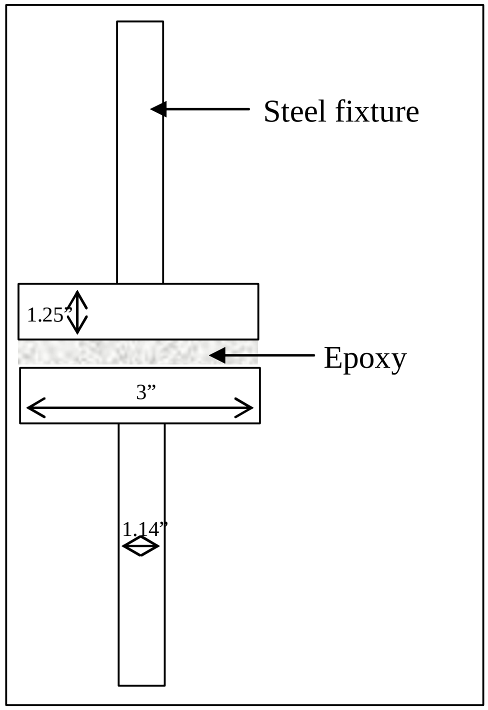

Figure 2.1: Fixture for testing epoxy

Prior to each test, the platen faces were prepared by sand blasting with a medium grit silica sand, removing dust with compressed air, and rinsing with reagent grade isopropyl alcohol. Three small pieces of 0.030 in (0.762 mm) shim stock were attached at the perimeter of one of the static condition platens with quick setting adhesive to provide a simulated crack when the two platens were put together. The platens were wrapped with plastic along with a pouch of desiccant until the time of the test, to prevent the prepared surfaces from rusting.

The fixture for cyclic displacement was aligned in the fatigue machine and the gap set to 0.030 in (0.762 mm) using a shim. An O-ring and adhesive tape were fitted around the bottom platen to create a reservoir to hold the excess epoxy that ran out of the simulated crack. A temperature chamber was then positioned around the fixture. For the static condition, the fixture was placed on the bottom of the chamber as shown in Figure 2.2. Both sets of fixtures were allowed to equilibrate to the target temperature for a minimum of one hour. The temperature of the chamber was controlled with a thermoelectric cooler (and heater) to within 0.5^{o}F of the target temperature.

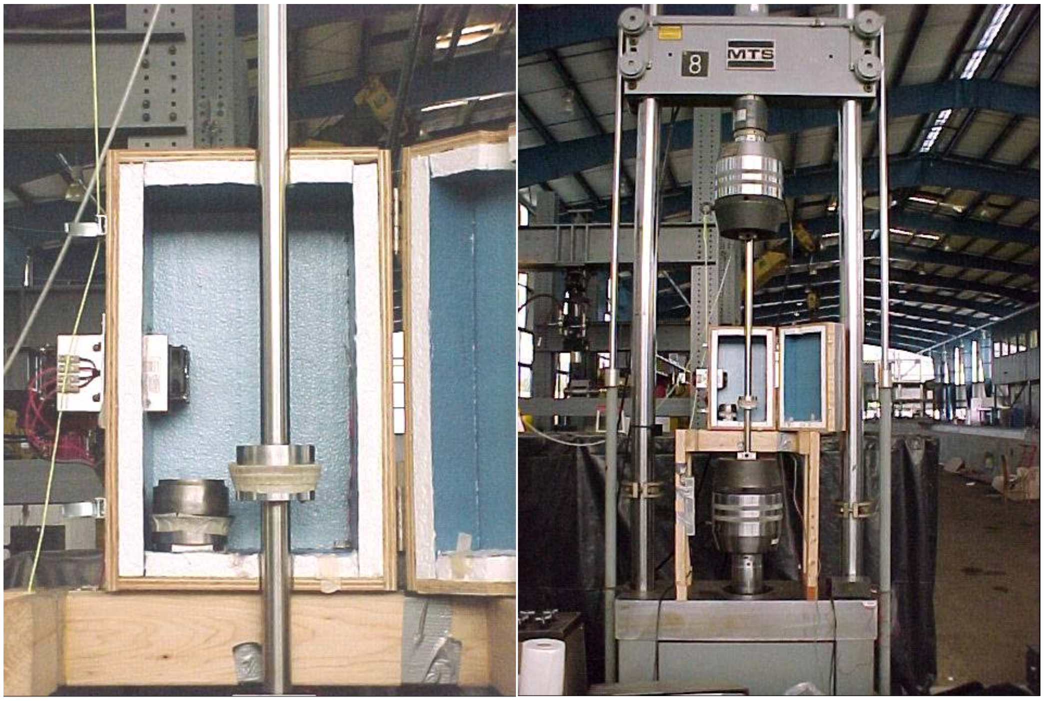

Figure 2.2: Arrangement of the test fixtures in the temperature chamber and in the fatigue machine

After equilibrating:

- the temperature chamber was opened,
- the opposing platens for both sets of fixtures were separated,
- mixed epoxy was spread over the face of the bottom platens,
- the opposing platens were placed back together,
- and the temperature chamber door was closed, and the hold time was started.

After the hold time elapsed, the fatigue machine began 96 hours of cycling at 1 Hz, with a displacement of 0.003 in (0.0762 mm). Following the cycling, both specimens remained in the chamber at the target temperature under static conditions for a balance of time to achieve a total of seven days in the chamber. The specimen pairs were removed from the chamber and maintained at ambient laboratory temperature until the bond strength was measured by pulling the platens apart in a universal tensile testing machine.

Bond strength, as used in this report, refers to the stress required to pull the platens apart. No attempt was made to assign values to the strength of the bond between the epoxy and the surface of the platen or the tensile strength of the bulk epoxy between the platens.

Three epoxies for structural crack injection are on the ODOT Qualified Products List. One of the three would have set up too quickly to have been compatible with the test procedure used in this study. For the two remaining epoxies, an initial screening using the testing protocol at 65^{o}F (18.3°C) was conducted in order to select one for the remainder of the tests. The epoxy with the greatest decrease in bond strength, due to cyclic displacement, was used for the DOE.

A Central Composite Design was used to develop a response surface incorporating the factors temperature and hold time. The responses were bond strength, difference in bond strength between the cycled and baseline conditions, fractional bond strength change, and the bond strength of the cycled condition normalized with respect to the static condition. The DOE software application Design Expert was used to evaluate the DOE.

2.3 INJECTION EXPERIMENTS

An attempt was made to investigate the effect of temperature and injection pressure on the extent of filling a crack. The intent was to conduct a series of injection trials at various temperatures and injection pressures and then measure the fraction of the crack surface covered with epoxy after each trial. A relationship could then be established between crack fill, as a function of temperature, and injection pressure.

2.3.1 Patio Block Experiment

A simulated crack was constructed using patio blocks. It was felt that the rough surface of the blocks would provide friction to the moving epoxy, somewhat similar to the surface of an actual crack. There was some concern that the patio blocks would be to porous and would not allow the epoxy to be pressurized during injection. Spacers 0.010 in (0.254 mm) thick were used between the mating surfaces to create the simulated crack. A hole for the injection port was drilled into the blocks and a bead of silicone caulk was placed around the perimeter of one side of the blocks. The blocks were then clamped together and the injection port was installed with epoxy. Injection pressure was achieved by pressurizing a reservoir of epoxy with compressed air. Unfortunately, the porosity of the blocks proved to be fatal because the epoxy was pushed through the blocks and around the silicone seal.

2.3.2 Acrylic Sheet Experiment

A similar approach used 0.375 in (9.53 mm) acrylic sheets backed by 0.75 in (19.05 mm) plywood in place of the patio blocks. The mating surfaces of the sheets were abraded with a wire brush and the perimeter was sealed with epoxy. This attempted to explore whether a simple fixture could be built to withstand crack injection, though epoxy flowing across acrylic would not necessarily relate to epoxy flowing across concrete. The seal along the perimeter failed during injection of the epoxy. No further trials were made to investigate the injection parameters on crack fill.

3.0 RESULTS

3.1 STATE-OF-THE-PRACTICE

Twenty states and Canadian provinces responded to the questionnaire, as shown in Appendix A. No state had conducted an investigation into the effect of live loads during curing on epoxy performance. Traffic restriction during curing of the epoxy ranged from none, to no traffic during the curing. No formal investigation of injection parameters had been done by any of the states that responded to the questionnaire. Coring conducted by some of the states showed that crack fill ranged from incomplete to complete.

3.2 CURING EXPERIMENTS

Initially, the screening trials for the two epoxies were configured to start cycling immediately after placing the epoxy between the platens. The first three tests using this approach showed that the epoxy was squeezed out of the simulated crack resulting in much of the platen faces being coated with epoxy, but not bonded to the adjacent face. The hypothesis was that, as the viscosity increased during curing, a point in time was reached in which the epoxy was squeezed out to the reservoir during the compression cycle and could not flow back into the gap fast enough to keep up with the 1 Hz cycling of the fixture. One would expect a similar mechanism to occur in a crack opening and closing on a bridge subjected to live load soon after injection.

The test protocol was changed to include a minimum 6-hour hold time before cycling began. The intent of the hold time was to allow the viscosity of the epoxy to increase so it would be compressed rather than squeezed out of the simulated crack.

The results of the DOE runs are shown in Table 3.1. The static condition always had a higher bond strength than the cycled condition. In addition, the fracture surface of the static condition exhibited debonding between the epoxy and the platen surface of up to 68% of the surface area. The cycled condition generally showed little or no debonding. The extent of debonding for each run is given in Appendix B, and examples of the fracture surfaces are shown in Figure 3.1.

Table 3.1: Results of DOE runs

Randomized Run Order	Factors		Responses							
	Temperature °F (°C)	Hold Time (Hours)	Static Bond Strength		Cycled Bond Strength		Bond Strength Difference		Bond Strength Decrease (%)	Cyclic/ Static
			psi	MPa	psi	MPa	psi	MPa		
1	68 (20.0)	39	3483	24	3264	22.5	219	1.50	6.29	0.937
2	45 (7.22)	39	2861	19.73	2160	14.89	701	4.84	24.5	0.755
3	68 (20.0)	39	4287	29.56	3124	21.54	1163	8.02	27.1	0.729
4	83 (28.3)	16	3350	23.1	2720	18.75	630	4.35	18.8	0.812
5	68 (20.0)	6	3402	23.46	48	0.33	3354	23.13	98.6	0.0141
6	68 (20.0)	39	3931	27.1	2708	18.67	1223	8.43	31.1	0.689
7	90 (32.2)	39	4183	28.84	2687	18.53	1496	10.31	35.8	0.642
8	68 (20.0)	39	3857	26.59	2084	14.37	1773	12.22	46.0	0.540
9	83 (28.3)	62	3375	23.27	2057	14.18	1318	9.09	39.1	0.609
10	68 (20.0)	72	3429	23.64	2487	17.15	942	6.49	27.5	0.725
11	52 (11.1)	62	2247	15.49	2054	14.16	193	1.33	8.59	0.914
12	68 (20.0)	39	3180	21.93	2064	14.23	1116	7.70	35.1	0.649
13	52 (11.1)	16	3551	24.48	2505	17.27	1046	7.21	29.5	0.705

Figure 3.1: Fracture surfaces of static (left) and cycled (right) specimens from run 10 in Table 3.1.

Run 5 in Table 3.1, with a 6-hour hold time, exhibited incomplete bonding between the opposing surfaces. Consequently, the bond strength for the cycled condition was very low. The 6-hour hold time was not adequate for the epoxy to set as intended, based on the trials conducted prior to the start of the DOE.

4.0 DISCUSSION

Except where stated, the discussion and conclusions from this research were based on one epoxy resin. The results are assumed to reflect general epoxy behavior. Incorporating multiple resins into the experimental design would have significantly increased the number of runs and the duration of the project.

The pre-DOE tests and run 5 of the DOE clearly showed that opening and closing of the simulated crack before the epoxy has set can cause the epoxy to be squeezed out of the space between the platens, resulting in little or no bonding between the opposing faces. The six hour hold time, before cycling, was at the critical time needed at the 65-68°F (18.3-20°C) temperatures to avoid the pumping effect for both the Eva-Pox® Resin 4 and the Concresive® 1360 epoxies. Both epoxies had one test after the hold time that exhibited unbonded platens and one test that showed bonded platens. Because the effect was observed in two epoxies, it is reasonable to expect similar behavior in all epoxies. Furthermore, the pumping effect could take place in actual injected cracks. Consequently, if cracks are active, traffic should be restricted so that the cracks do not move. The restriction should remain in place during the injection, and while the epoxy sets completely. The level of restriction could be determined by observing the crack motion of the most active cracks during light traffic conditions. If traffic, especially trucks, in far lanes do not cause crack motion, then diverting traffic to those far lanes may be satisfactory.

The epoxy manufacturer should supply data, or provide guidance, on the set time as a function of temperature. Many epoxies state the tack-free or set time at one specific temperature, but a rule of thumb is that the set time is doubled for every 18°F (7.8°C) decrease in temperature, and conversely set time is halved for every 18°F (7.8°C) increase in temperature. Set time can be estimated for a specific temperature simply by spreading a thin layer of epoxy resin over a surface, and recording the time until the epoxy is no longer sticky to the touch. The epoxy and surface must be maintained at a constant temperature either in a temperature chamber or under constant ambient temperature conditions. For establishing the traffic restriction time on crack injection projects, the set time should be estimated based on the coolest expected temperature of the concrete.

The static condition consistently showed substantially more debonding than the cycled condition, but the bond strength of the static condition was always greater than that of the cycled condition. For the DOE experiments, excluding run 5, the bond strength of the cycled condition was 28% less than the bond strength of the static condition. A t-test verified that the lower bond strength of the cycled specimens was statistically significant (Appendix C). This result indicates that early-age cycling reduces the bulk tensile strength of the epoxy. However, whether repeated straining during curing was responsible for the decrease in strength or whether repeated straining of fully cured material would also reduce strength, was not investigated. This research did not investigate the long term fatigue performance of epoxy exposed to years of traffic.

Though bond strength decreased as a result of cyclic straining, the strength was still substantially greater than the tensile strength of concrete. Assuming a compressive strength of 6000 psi (41.37 MPa) for concrete and a tensile strength value equal to approximately 15% of the compressive strength, then the tensile strength of concrete is around 900 psi (6.21 MPa). Except for run 5, all of the bond strengths for the cycled specimens were greater than 2000 psi (13.79 MPa) after 345,600 cycles, with each cycle producing displacement equal to 10% of the nominal simulated crack width (5% in compression and 5% in tension). From a practical standpoint, the test runs did not show that cyclic straining of set epoxy will affect the performance of epoxy that has been properly injected into concrete cracks. However, though the epoxy may have adequate tensile strength, a structural element with incomplete crack fill is likely to have less than the intended capacity.

Analysis of the DOE for the two factors and five responses in Table 3.1 resulted in no mathematical model up to a quadratic that was significant relative to the noise in the data. Consequently, the temperature at which curing occurs, and the amount of quiescent time before the epoxy is exposed to cyclic strain, has little or no effect on bond strength within the range of parameters tested in this DOE; with the assumption that the epoxy has set before it is exposed to strain.

5.0 CONCLUSIONS

Traffic should be restricted during injection, and while the epoxy sets up to prevent crack motion that can result in unbonded surfaces. Traffic restrictions need only to remove vehicles from the bridge that produce crack opening and closing. Epoxy set time data for the lowest temperature expected in the concrete needs to be supplied from the epoxy manufacturer, or other sources, in order to determine the duration of the traffic restriction.

After setting, epoxy exposed to large numbers of strain cycles during curing will have reduced tensile strength. However, the tensile strength of the epoxy will still be substantially greater than the tensile strength of concrete.

After setting, but within seven days of injection, temperature and time before the epoxy is subjected to cyclic strain have no effect on the ability to bond two surfaces together. Consequently, there is no advantage to restricting traffic once the epoxy has set up.

6.0 RECOMMENDATIONS

The attempt to determine the effect of injection variables on the extent of crack fill was not successful in this project. Nevertheless, such an effort should be pursued to have a basis for specifying crack injection parameters that produce a high degree of crack fill. An investigation should be conducted on specimens that simulate actual field cracks, but at the same time, the tests need to be run so that the variables are controlled.

In order to specify quantitative thresholds for the injection variables, a set of experiments should be conducted that produces a response surface. Variables that would likely affect crack fill are crack size, injection pressure, and resin viscosity. Resin formulation, temperature, and the elapsed time after mixing affect the resin viscosity. To design a set of experiments that can produce a response surface with a reasonable number of runs, the number of variables should be limited to three. Crack size could remain constant under the assumption that crack injection projects require injection of cracks down to a set minimum width. Also, injection pumps often mix the resin components at the nozzle, which means the elapsed time after mixing is close to zero (low pressure, slow injection systems notwithstanding). Therefore, the three variables could be: injection pressure, freshly mixed viscosity (determined by the specific resins being tested), and temperature.

A concept for the crack specimen is shown in Figure 6.1. The concrete slab needs to be large enough to produce a crack that can not be completely filled with any combination of injection variables under investigation. A 1 ft x 3 ft (30.48 cm x 91.44 cm) crack surface should be adequate. After the concrete slab is split with wedges to create the crack, the threaded bars and nuts are used to set and maintain the crack width. Crack preparation for injection would follow standard industry practice. A temperature chamber would be required to achieve the target temperatures of the specimens prior to injection. After injection, but before the resin sets, the nuts are removed and the two halves are split apart in order to measure the fraction of the crack that is filled. One specimen would be required for each run in the experimental design.

A concrete block with a cast groove around the perimeter as a crack guide is loaded through wedges to crack the concrete. The block includes steel eyes that are cast in place. After cracking, nuts on the threaded bars are tightened against the eyes to maintain the crack width.

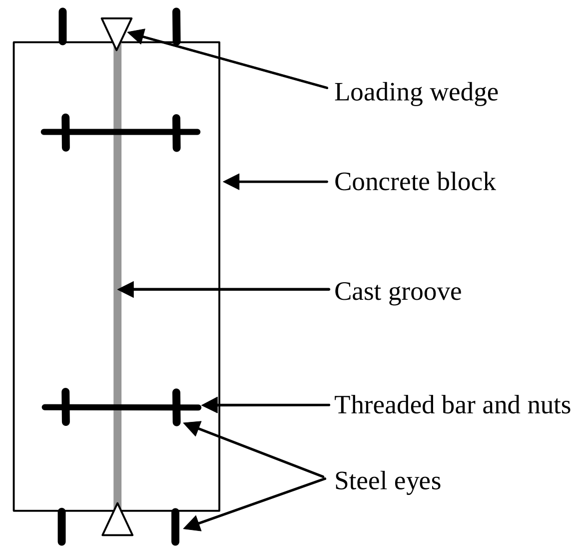

Figure 6.1: Proposed concrete crack specimen

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APPENDIX A

QUESTIONNAIRE SENT TO STATE TRANSPORTATION AGENCIES AND RESPONSES

The State of Oregon uses epoxy crack injection to improve the structural integrity of reinforced concrete bridges. However, we have had cases in which cores removed from injected structures have shown incomplete crack fill. In addition, we do not limit traffic on bridges during or immediately after injection. We do not know the effect live load has on curing and the performance of the epoxy. Consequently, the Research Group has been asked to investigate the effect of injection parameters on crack fill and the effect of traffic loading on the integrity of curing epoxy.

In order to understand the state-of-practice for crack injection, the ODOT Research Group would like your input on the following questions:

**Has your state researched the effect of live load on the performance of injected epoxy?

**If yes, what were the results? If there is a report, please send it to me.

**Does your state restrict traffic on bridges while injected epoxy cures? **If yes, what are the restrictions?

**Has your state investigated the effect of injection parameters such as temperature, injection pressure on achieving complete fill of cracks?

**If yes, what were the results? If there is a report, please send it to me.

**Does your state use specifications for injection parameters other than those provided by the manufacturers?

Summary Table of Responses

State	Live load on performance of injected epoxy	Restrict traffic for epoxy injection	Investigated injection parameters	Custom injection specifications other than manufacturers' specifications
Louisiana	None	All injection done on collision repairs, so bridges were closed. Not done on load-related cracks because new cracks will form adjacent to filled cracks.	Coring has shown good penetration and fill. No formal investigation	None
Idaho	None	For severe cracks, traffic restricted to adjacent lanes during injection and curing.		Idaho specifications require a contractor (or maintenance forces) to start injection in the lowest possible port until the pump reaches it's maximum pressure. Each port that the epoxy is extruded while pumping is plugged until the pump

				has met it's greatest effort. Then the injection effort moves to the last port the epoxy material was expelled from. The pumping effort then continues at that point until the pump is maxed out again.
Nevada	Repairs have primarily been limited to new bridges so we've not experienced problems with live load effects.	None	None	Provided
Virginia	None	None	None	Provided
Vermont	No experience			
Indiana	None	Traffic is restricted during curing. Specification provided	None	Provided
Colorado	Limited experience	None	None	None
Wyoming	None	Traffic may be slowed depending upon the application. If substructure units are being injected, traffic is usually left unrestricted. If injection is occurring in an area prone to movement due to live load, such as a void between a girder top flange and bridge deck, than traffic may not even be allowed over the area by restricting half the bridge deck.	None	None
Minnesota	None	None	None	None
North Carolina	None	None	None	Provided
Maryland	None	None	None	Provided
Arkansas	None	None	None	None
Oklahoma	None	The Restriction and cure time shall be described by the Manufacture's Recommendations and/or specifications.	Our Specifications described all of the parameter, limits and guidelines in Sec. 520.02, 520.03 and 520.04	Described in previous question

		We do not take live load off the bridges for the epoxy to cure.		
Washington	None	None	None	None
Alberta	None	Traffic is usually restricted during injection and curing - live loads are generally diverted from the girders subject to repair.	Unofficial evaluations have been made several times on structures that sustain somewhat repetitive or multiple collision impacts - and, results are favorable that full crack depth and fissure penetration had been attained. Curing concerns have not been apparent, or an issue to date.	generally covers epoxy resin injection requirements in special provisions of contracts.
Florida			have had reports where voids end up in the final product. It has been mostly attributed to viscosity problems of the material.	
British Columbia	None	None	None. We have used epoxy injection for repair of decks and pier caps. We have taken cores in order to verify results. There have been cases where the crack filling was not complete.	Our specifications are typically based on manufacturer's specifications and ASTM C 881.
Connecticut	None. Uses vacuum injection of methyl methacrylate	None	None	N/A
Kentucky	None	1 case: restricted from 22 to 10 tons	None	None
Delaware	None	None	None	None

Nevada

For crack repair by epoxy injection, use a two-component solventless, low viscosity, liquid adhesive epoxy specifically formulated for injection into cracks. Epoxy shall conform to AASHTO M235 Type IV, Grade 1, 2, or 3, Class A, B, or C.

Use a surface seal epoxy of adequate strength to hold injection ports firmly in place and to resist injection pressures to prevent leakage during injection.

Prior to the start of epoxy injection, submit the following for approval:

1. Specifications on the epoxy materials and injection equipment.
2. Material Safety Data Sheets.
3. A written procedure for the injection process.

Clean the areas surrounding the crack of deteriorated concrete. Remove contaminants that may be detrimental to adhesion. The crack may be ruffed or "veed" to accommodate insertion of injection ports. Perform drilling of the crack for injection ports with a vacuum attached swivel drill chuck. The crack may be slotted to facilitate installation of injection tees. Seal the surface of the crack and the area surrounding the entry ports with an approved epoxy. Use approved entry port devices spaced at intervals to insure full penetration of the epoxy.

Accomplish injection of the epoxy by a machine capable of metering and mixing the component proportions with a tolerance of " 2.0%. Operate the injection machine at a nozzle pressure of approximately 172 kPa (25 psi).

Begin injection of epoxy at the lower entry port and continue until appearance of epoxy at the adjacent port. Perform epoxy injection in the next adjacent port where epoxy has appeared. Continue this operation until the cracks are completely filled. Upon completion of the injection of epoxy and after initial cure, remove the entry ports and patch the area.

Virginia

412.02-Materials.
(a) **Epoxy and mineral fillers** shall conform to the requirements of Section 243. Epoxy for epoxy mortar shall be Type EP-5. Epoxy used for crack repair shall be Type EP-4 or EP-5, low viscosity.

SECTION 243-EPOXY-RESIN SYSTEMS

243.01-Description.
These specifications cover epoxy-resin systems to be used for all applications requiring bonding of various materials or as patching or overlay of concrete slabs.

243.02-Detail Requirements.
Epoxy-resin materials shall conform to the applicable requirements of Tables II-19, and II-21. The infrared spectrum for each component shall essentially match that of
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TABLE II-19
Requirements: Component A
Type EP-3B EP-3T EP-4 EP-5 EP-6
Property Max. Max. Max. Max. Max.
Epoxide equivalent 245 220 225 270 245
253
243.02

TABLE II-21
Requirements: Mixed Epoxy Systems
EP-3B Red EP-3T Gray EP-4 Straw EP-5[1] Straw EP-6 Lt. Straw CTE Black
Property Min Max Min Max Min Max Min Max Min Max Min Max
Pot life at 75°F 40 65 40 65 35 55 35 35 20 30 20 40
Tensile strength (psi) at 75°F - - - - 3,000 - 2,000 - 1,500 - 400 -
Tensile elongation (%) at 75°F - - - - 1 3 5 15 5 15 30 -
Water absorption (Max. %) - 0.8 - 0.8 - 0.8 - 0.8 - 0.8 - 0.8
2 in Cubes compressive (psi,
24 hr, dry) (min.) - - 6,000 - -
Strength (psi, 48 hr, wet) (min.) - - 7,000 4,000 4,000 -
Bond strength: (7 day) Hardened
concrete to hardened concrete or
fresh concrete (psi min.) 3,000 3,000 3,000 - 3,000 2,500
Ash content (%) 20 30 10 20 - 0.5 - 0.5 5 15 - 5.0
Viscosity
Poises 40 100 40 150 20 40 10 25 - -
Spindle No. 4 4 3 3 Gel
Speed 10 or 20 10 or 20 20 20
Volatile content (max. %) 6.0 3.0 3.0 3.0 20.0

1Epoxy system EP-5LV shall have the same requirements as epoxy system EP-5 except that the viscosity shall be less than 9.0 poises.

the standard infrared spectrum for the particular component as specified in AASHTO T237, Sections 4 and 5.

(a) **Epoxy Systems:**

1. **Types EP-3B and EP-3T** shall be 100 percent reactive high build coatings designed as a two coat (minimum) system for protection of concrete exposed to splash zones and tidal water. Type EP-3B shall be the prime or base coat, and Type EP-3T shall be the finish or topcoat.
2. **Types EP-4, EP-5, and EP-6** shall be moisture insensitive systems designed for structural bonding, sealing, and grouting of dry, damp, or wet structural material free from standing water. Mortar shall be prepared by mixing 3 1/4 parts by volume of loose oven-dried sand

to 1 part of premixed Type EP-4 or EP-5 epoxy; however, Type EP-6
shall be mixed on a 1:1 ratio.
Mortars shall be mixed to a uniform consistency.
Type EP-4 shall be a high modulus, rigid, general purpose adhesive
with a tensile elongation of 1 to 3 percent. Type EP-4, low viscosity,
shall be used to seal rigid cracks.
Type EP-5 shall be a low modulus patching, sealing, and overlay
adhesive with an elongation of at least 10 percent. When used as a
penetrating sealer and to repair nonrigid cracks, Type EP-5 shall be
of a low viscosity.
Type EP-6 shall be a low modulus, nonsagging, flexible adhesive
with an elongation of at least 5 percent. Type EP-6 shall be used for
bonding or repairing damp and underwater surfaces where a nonsagging,
low modulus material is required.
(b) **Classes:** Epoxy resin shall be formulated for use at specific temperatures.
Three classes of systems are defined according to the range of temperatures
for which they are suited. The controlling temperature shall be that of the
surface of the hardened concrete to which the bonding system is applied.
Where unusual curing rates are desired and upon the approval of the Engineer,
a class of bonding agent may be used at a temperature other than that
for which it is normally intended. The class and gel temperature shall be
as follows:
1. **Class A:** for use below 40 degrees F
2. **Class B:** for use between 40 degrees F and 60 degrees F
3. **Class C:** for use below 60 degrees F

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243.02

(c) **Mixing Epoxy:** Epoxy resin shall be furnished in two components for
combining in accordance with the manufacturer's instructions immediately
prior to use. Component A shall contain a condensation product of
epichlorohydrin with bisphenol A and shall conform to the requirements
of Table II-19. Component B shall conform to the requirements of Table
II-20 and shall contain one or more hardening agents that will cause the
system to polymerize and harden, on mixing with Component A in accordance
with Table II-21. Thixiotropic agents used to control viscosity will
be permitted in accordance with the manufacturer's recommendations. If
the mixture proportion of component A to component B exceeds 2:1, only
complete units as packaged by the manufacturer shall be used.
Contents of the separate packages containing Components A and B shall
be thoroughly stirred prior to use. The same paddle shall not be used to stir
Component A that is used to stir Component B. The Contractor shall dispose
of solvents used for cleaning in accordance with applicable Virginia
Department of Waste Management policies and procedures. Components
A and B shall be stored between 65 degrees F and 80 degrees F for at least
2 hours before use. Epoxy components may be heated in hot water or by
indirect heat prior to mixing to bring them to the required temperature.
Solvents and thinners shall not be used except for cleaning equipment.
Mixing of epoxy components shall be in accordance with the manufacturer's
instructions.
When mineral fillers are specified, they shall be inert and nonsettling or
readily dispersible. Materials showing a permanent increase in viscosity
or the settling of pigments that cannot be readily dispersed with a paddle
shall be replaced at the Contractor's expense. At least 95 percent of the
filler shall pass the No. 300 sieve.
(d) **Aggregates:** Aggregate for surface application work shall be nonfriable,

nonpolishing, clean, and free from surface moisture. Silica sand having a
well-rounded particle shape shall be used. Aggregates that will be
exposed to traffic shall have a Mohs scale hardness of at least 7. In surface
applications, the aggregate shall be applied on the epoxy surface in
excess of the amount necessary to cover the surface, shall be sprinkled or
dropped vertically in such a manner that the level of epoxy mixture is not
disturbed, and shall be applied within 5 minutes after application of the
epoxy. At temperatures below 70 degrees F, a maximum of 10 minutes
will be allowed. The grading analysis of the fine aggregate (silica sand)
shall conform to the requirements of Table II-22.

243.03-Handling and Storing Materials.

The two components of the epoxy resin system shall be furnished in separate containers
that are nonreactive with the materials. The size of the containers shall be

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243.03

such that the recommended proportions of the final mixture can be obtained by combining
one container of Component A with one container of Component B. The size
of the container shall be not more than 10 gallons. When less than one complete unit
is used, each component shall be measured within ±2 percent of the volume required.
Batches of less than 6 fluid ounces shall be measured within ±1 percent.
Containers shall be identified as "Component A-Contains Epoxy Resin" and
"Component B-Contains Hardener" and shall show the type, class, and mixing
directions. Each container shall be marked with the name of the manufacturer; class,
batch, or lot number; date of packaging; date of shelf life expiration; pigmentation,
if any; and the quantity contained in pounds and gallons.

243.04-Acceptance.

Shipments of less than 15 gallons may be accepted upon certification. The Contractor
shall submit a certification from the manufacturer that Components A and B
conform to these specifications. The certification shall consist of a statement by the
manufacturer that Components A and B have been sampled and tested. The certification
shall be signed by an authorized agent of the manufacturer and contain actual
results of tests performed in accordance with the methods specified herein.
For shipments of 15 gallons or more, at least one random test sample of each component
from each batch or lot number will be taken by the Department. The quantity
of Component A required to react with 1 quart of Component B will be a sufficient
sample for the tests specified. Components shall be furnished in as few
different batches or lots as possible.

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243.03

TABLE II-22

Fine Aggregate (Silica Sand)

Amounts Finer Than Each Laboratory Sieve

(Sieve Opening) (% by Weight)

Grading No. 8 No.16 No. 20 No. 30 No. 40 No. 100

D Min 100 50 ± 10 Max 3 Max 1

E Min 100 99 ± 1 95 ± 5 Max 10

Grading D aggregate shall be used in Class I waterproofing and other skid-resistant applications.
Grading E aggregate shall be used in epoxy patching mortars and loop detector
sealants. Aggregates shall be oven dried.

Tests will be performed in accordance with the following methods:

Characteristics Test Method Other

Viscosity ASTM D2393, Model RVF Determination to be

Brook-field visco-meter made at

Class A-32°F

Class B-50°F

Class C-77°F

Epoxide equivalent ASTM D1652 and VTM-43
Volatile content ASTM D1259, Method B, for Sample cured 4 days at
mixed system room temperature and
weighed on previously
weighed metal foil
Filler content VTM-43
Ash content ASTM D482
Pot life AASHTO T237 Determination to be
made at
Class A-32°F
Class B-50°F
Class C-75°F
Tensile strength ASTM D638
Bond strength VTM-41
Compressive strength VTM-41
Water absorption ASTM D570
Thermal shear VTM-42

Indiana

727-B-012
1 of 2
CONCRETE REPAIR BY EPOXY INJECTION
The Standard Specifications are revised as follows:
SECTION 727, BEGIN LINE 1, INSERT AS FOLLOWS:

SECTION 727 -- - CONCRETE REPAIR BY EPOXY INJECTION

727.01 Description. This work shall consist of furnishing all supervision, labor, materials, and equipment to structurally rebond concrete cracks, fractures, or delaminations by means of an epoxy injection system.

727.02 Approvals. Prior to the start of the work, the Contractor shall submit a certification which indicates that the firm has been engaged in this type of work for not less than five years. The certification shall also indicate that the personnel performing the repair shall have a minimum of five years experience with the epoxy injection system.

The epoxy injection system proposed for use shall be subject to approval prior to the start of the repair work. One copy of comprehensive preparation, mixing, and application instructions shall be furnished. Such instructions shall have been developed especially for use with the proposed epoxy injection system.

727.03 Construction Requirements. The location and extent of cracks to be repaired by epoxy injection will be determined.

The work shall be performed with 2-component automatic metering and mixing equipment.

Concrete surfaces adjacent to the cracks shall be cleaned to the extent necessary to achieve adequate bond of the surface seal material. Entry ports shall be provided along the crack at intervals determined in the field to ensure full depth penetration of the injection resin. Surface seal shall be applied between entry ports, and on both faces of through cracks when possible.

Epoxy injection shall begin at the lower entry port and continue until there is an appearance of epoxy at the adjacent entry port. Injection shall continue until all cracks are completely filled. If port to port travel is not apparent, the work shall be stopped immediately. The Engineer shall be notified.

Upon completion of the injection, the adhesive shall be permitted to cure for sufficient time to permit removal of surface seal without draining or runback of material from the cracks. Surface seal material and injection adhesive runs or spills shall be removed from concrete surfaces. The face of the crack shall be finished flush to the adjacent concrete. The face of the concrete shall show no indentations or protrusions caused by the placement of entry ports.

727.04 Method of Measurement. Furnishing equipment for epoxy injection will not be measured for payment. Crack preparation for epoxy injection will be measured
Rev. 1-4-99
by the meter (linear foot) of prepared crack. Epoxy material will be measured by the liter (gallon) placed.

727.05 Basis of Payment. This work will be paid for at the contract lump sum price for epoxy injection, furnishing equipment. Crack preparation will be paid for at *the contract unit price per meter (linear foot) for epoxy injection, crack preparation. Epoxy resin adhesive will be paid for at the contract unit price per liter (gallon) for epoxy injection, epoxy material.*

Payment will be made under:

Pay Item Metric Pay Unit Symbol (English Pay Unit Symbol)
Epoxy Injection, Crack Preparation ....m LFT)
Epoxy Injection, Epoxy Material .... L (GAL.)
Epoxy Injection, Furnishing Equipment... LS

SECTION 909, AFTER LINE 832, INSERT AS FOLLOWS:

909.12 Epoxy Resin Additives for Injection into Concrete. The epoxy resin adhesive shall be of low enough viscosity such that it flows to the next open port in the surface seal material. The adhesive shall be capable of penetrating crack widths down to 125 :m (0.005 in.). The adhesive shall be capable of bonding to dry or damp surfaces. The adhesive shall exhibit a slant shear strength exceeding the concrete strength when tested fully cured in accordance with AASHTO T 237.

The surface seal material shall have adequate strength to hold injection fittings firmly in place and to resist injection pressures adequately to prevent leakage during injection.

The epoxy resin adhesive for injection shall be covered by a type C certification in accordance with 916.

North Carolina

EPOXY RESIN INJECTION (10-12-01)

GENERAL

For repairing cracks, an approved applicator is required to perform the epoxy resin injection. Make certain the supervisor and the workmen have completed an instruction program in the methods of restoring concrete structures utilizing the epoxy injection process and have a record of satisfactory performance on similar projects.

The applicator furnishes all materials, tools, equipment, appliances, labor and supervision required when repairing cracks with the injection of an epoxy resin adhesive.

SCOPE OF WORK

[FOR EXAMPLE SEE LAST PAGE OF THIS SPECIAL PROVISION]

COOPERATION

Cooperate and coordinate with the Technical Representative of the epoxy resin manufacturer for satisfactory performance of the work.

Have the Technical Representative present when the job begins and until the Engineer is assured that his service is no longer needed.

The expense of having this representative on the job is the Contractor's responsibility and no direct payment will be made for this expense.

TESTING

The North Carolina Department of Transportation Material and Tests Unit obtains test cores from the repaired concrete. If the failure plane is located at the repaired crack, a minimum compressive strength of 3000 psi (20.7 MPa) is required of these cores.

MATERIAL PROPERTIES

Provide a two-component structural epoxy adhesive for injection into cracks or other voids. Provide modified epoxy resin (Component "A") that conforms to the following requirements:

	Test Method	Specification Requirements
Viscosity @ 40 ± 3°F (4 ± 1°C), cps	Brookfield RVT Spindle No. 4 @ 20 rpm	6000 - 8000
Viscosity @ 77 ± 3°F (25 ± 1°C), cps	Brookfield RVT Spindle No. 2 @ 20 rpm	400 - 700
Epoxide Equivalent Weight	ASTM D1652	152 - 168
Ash Content, %	ASTM D482	1 max.

Provide the amine curing agent (Component "B") used with the epoxy resin that meets the following requirements:

	Test Method	Specification Requirements
Viscosity @ 40 ± 3°F (4 ± 1°C), cps	Brookfield RVT Spindle No. 2 @ 20 rpm	700 - 1400
Viscosity @ 77 ± 3°F (25 ± 1°C), cps	Brookfield RVT Spindle No. 2 @ 20 rpm	105 - 240
Amine Value, mg KOH/g	ASTM D664*	490 - 560
Ash Content, %	ASTM D482	1 max.
* Method modified to use perchloric acid in acetic acid.		

Certify that the Uncured Adhesive, when mixed in the mix ratio that the material supplier specifies, has the following properties:

Pot Life (60 gram mass)

@ 77 ± 3°F (25 ± 1°C) 15 minutes minimum

@ 100 ± 3°F (38 ± 1°C) 5 minutes minimum

Certify that the Adhesive, when cured for 7 days at 77 ± 3°F (25 ± 1°C) unless otherwise specified, has the following properties:

	Test Method	Specification Requirements
Ultimate Tensile Strength	ASTM D638	7000 psi (48.3 MPa) min.
Tensile Elongation at Break	ASTM D638	4% max.
Flexural Strength	ASTM D790	10,000 psi (69.0 MPa) min.
Flexural Modulus	ASTM D790	3.5 x 10^5 psi (2413.2 MPa)
Compressive Yield Strength	ASTM D695	11,000 psi (75.8 MPa) min.
Compressive Modulus	ASTM D695	2.0 - 3.5 x 10^5 psi (1379.0 - 2413.2 MPa)
Heat Deflection Temperature	ASTM D648*	125°F (52°C) min.
Cured 28 days @ 77 ± 3°F (25 ± 1°C)		135°F (57°C) min.
Slant Shear Strength, 5000 psi (34.5 MPa) compressive strength concrete	AASHTO T237	
Cured 3 days @ 40°F (4°C) wet concrete		3500 psi (24.1 MPa) min.
Cured 7 days @ 40°F (4°C) wet concrete		4000 psi (27.6 MPa) min.
Cured 1 day @ 77°F (25°C) dry concrete		5000 psi (34.5 MPa) min.

* Cure test specimens so that the peak exothermic temperature of the adhesive does not exceed 77°F (25°C).

Use an epoxy bonding agent, as specified for epoxy mortar, as the surface seal (used to confine the epoxy resin during injection).

EQUIPMENT FOR INJECTION

Use portable positive displacement type pumps with interlock to provide positive ratio control of exact proportions of the two components at the nozzle to meter and mix the two injection adhesive components and inject the mixed adhesive into the crack. Use electric or air powered pumps that provide in-line metering and mixing.

Use injection equipment with automatic pressure control capable of discharging the mixed adhesive at any pre-set pressure up to 200 ± 5 psi (1380 ± 35 kPa) and equipped with a manual pressure control override.

Use equipment capable of maintaining the volume ratio for the injection adhesive as prescribed by the manufacturer. A tolerance of ± 5% by volume at any discharge pressure up to 200 psi (1380 kPa) is permitted.

Provide injection equipment with sensors on both the Component A and B reservoirs that automatically stop the machine when only one component is being pumped to the mixing head.

PREPARATION

Follow these steps prior to injecting the epoxy resin:

- Remove all dirt, dust, grease, oil, efflorescence and other foreign matter detrimental to the bond of the epoxy injection surface seal system from the surfaces adjacent to the cracks or other areas of application. Acids and corrosives are not permitted.

- Provide entry ports along the crack at intervals not less than the thickness of the concrete at that location.
- Apply surface seal material to the face of the crack between the entry ports. For through cracks, apply surface seal to both faces.
- Allow enough time for the surface seal material to gain adequate strength before proceeding with the injection.

EPOXY INJECTION

Begin epoxy adhesive injection in vertical cracks at the lower entry port and continue until the epoxy adhesive appears at the next higher entry port adjacent to the entry port being pumped.

Begin epoxy adhesive injection in horizontal cracks at one end of the crack and continue as long as the injection equipment meter indicates adhesive is being dispensed or until adhesive shows at the next entry port.

When epoxy adhesive appears at the next adjacent port, stop the current injection and transfer the epoxy injection to the next adjacent port where epoxy adhesive appeared.

Perform epoxy adhesive injection continuously until cracks are completely filled.

If port to port travel of epoxy adhesive is not indicated, immediately stop the work and notify the Engineer.

FINISHING

When cracks are completely filled, allow the epoxy adhesive to cure for sufficient time to allow the removal of the surface seal without any draining or runback of epoxy material from the cracks.

Remove the surface seal material and injection adhesive runs or spills from concrete surfaces.

Finish the face of the crack flush to the adjacent concrete, removing any indentations or protrusions caused by the placement of entry ports.

BASIS OF PAYMENT

Payment for epoxy resin injection will be at the contract unit price per linear foot (meter) for “Epoxy Resin Injection”. Such payment will be full compensation for all materials, tools, equipment, labor, and for all incidentals necessary to complete the work.

EXAMPLE

2.0 SCOPE OF WORK

Using Epoxy Resin Injection, repair all cracks 5 mils (125 μm) wide or greater in the interior bent columns and caps, in the ends of the girders, in the cantilevered portion of the ends of the girders, and in the cantilevered portion of the superstructure deck on the downstream side.

Repair the column cracks to the top of the footings. Make the underwater repairs when water surface elevation is low and the water is still. For underwater repairs, use manufacturer recommended materials.

Repair any crack, void, honeycomb or spall area unsuitable for repair by injection with epoxy mortar.

NOTE: This part of the Special Provision must be written for each project.

CATEGORY 400
SECTION 481 — PRESSURE INJECTED EPOXY CRACK REPAIR

481.01 DESCRIPTION. Epoxy injection is limited to cracks with a maximum width of ¼ in. and shall include the furnishing and placing of an epoxy at crack locations shown on the Plans and as directed by the Engineer.

481.02 MATERIALS.

Epoxy grout	902.11(d)

The epoxy resin shall be conform to C 881, Type I. The grade shall be submitted for the Engineer's approval after the Contractor's analysis of areas to be injected.

The system shall be moisture insensitive and shall not be used when the ambient or concrete temperature is 50 F or below, nor temperatures lower than recommended by the manufacturer.

The expiration date of acceptance of this material shall be one year after the date of manufacture. Any unauthorized tampering or breaking of the seals on the containers between the time of sampling and delivery to the job site will be cause for rejection of the material.

481.03 CONSTRUCTION. The locations for the pressure injection of cracks will be delineated by the Engineer.

The Contractor shall ensure that the epoxy manufacturer's technical representative will be present for the duration of the injection process, and shall submit details of the proposed method of repairs and the injection procedure for the Engineer's approval.

The epoxy injection equipment shall be a positive displacement pump system. The system shall have a suitable mixing chamber where the epoxy components are accurately metered and thoroughly mixed immediately prior to injection. A clear, legible, and accurate pressure gauge shall be located in the supply line adjacent to the mixing chamber.

The equipment shall also be capable of providing a continuous and uninterrupted pressure head to continually force the injection of epoxy into the cracks. Epoxy flow shall be capable of being fully controlled by the operator controls at the mixing chamber.

All working personnel shall be familiar with the equipment, materials and procedures to be used during the operation.

All materials and equipment, including backup equipment, shall be at the work site before injection operations begin. All equipment shall be in proper calibration and in good working order as determined by the Engineer.

Epoxy shall be injected only by the use of the automatic mechanical pumping, metering, and mixing equipment described above. Pressure pot systems and caulking guns or grease guns will not be permitted.

The two components shall be mixed in conformance with the manufacturer's recommendations. The ratio of the components shall be maintained within a tolerance of five percent.

Acceptable solvents used for cleaning shall include mineral spirits, methyl ethyl ketone, acetone, low boiling naphtha, xylene, and any other nonchlorinated solvent.

481.03.01 Port Installation. Prior to injection of the epoxy in the crack, a surface seal material shall be applied to the face of the crack to prevent the liquid resin from leaking out. The surface seal material shall be useable on vertical, horizontal and overhead applications and shall completely bridge the crack when applied to the face of the crack.

Openings to inject the epoxy shall be established through the surface seal material along the entire length of the crack and entry ports shall be provided. The holes shall be ¾ in. diameter, spaced 6 to 12 in. apart and be of sufficient depth to ensure maximum dissemination of the pressure of the epoxy throughout this area.

Inserts shall be set in drilled holes and the holes shall be cleaned to remove any dust or debris left by drilling operations. Special care shall be exercised to assure that oil or other contaminants are not introduced into the air feed hoses, or deposited on any air blown surfaces.

481.03.02 Injection. The epoxy shall be forced into the internal voids and cracks by means of hydraulic pressure to completely fill all internal voids. If the surface seal material has insufficient strength and adhesion to confine the injected epoxy until it has cured, the Contractor shall remove the surface seal material and furnish and place a new surface seal material at no additional cost to the Administration.

Before injecting any epoxy, the automatic mixing and metering pump shall be activated and approximately 1 pt of the epoxy shall be mixed and pumped into a disposable container. The Engineer will observe this trial operation to determine that the equipment is working properly. If the equipment is not working properly, it shall be immediately repaired to full working condition or replaced with the backup equipment. If the backup equipment is used, additional and fully operable equipment shall be provided as its backup equipment.

The feed line from the mixing equipment shall be securely held or properly attached to the port. The operator shall then initiate the epoxy injection in conformance with the manufacturer's recommendations.

Injection shall be started at the lowest row of holes and at the hole nearest the center line of structure. Injection shall continue at the first port until the epoxy begins to flow out of the port at the next highest elevation. The first port shall then be plugged and injection started at the second port until the adhesive flows from the next port. This sequence shall continue until the entire crack is repaired.

The injection procedure shall be monitored to ensure the epoxy flow does not cease before the injection epoxy exudes from the adjacent port. If the epoxy flow stops before epoxy appears at the adjacent port, the feed line shall be moved to the adjacent port and the port just used shall be sealed.

During the course of all operations, extreme care shall be given to observe for breaking out of epoxy. When breaking out occurs, the injection shall stop and the line shall be moved to another crack. Injecting may be resumed in the original location after a minimum elapse of 24 hours.

A continuous injection operation shall be accomplished by replenishing the epoxy supply tanks in the mixing equipment before they are exhausted. Each epoxy component shall be thoroughly stirred before adding it to its respective storage tank in the mixing equipment. No discontinuity of epoxy flow through the feed lines of either component shall be permitted.

Any work stoppage permitting mixed epoxy to remain in the injection equipment more than 15 minutes shall require cleaning the mixing chamber and all equipment in contact with the mixed epoxy. Quantities of epoxy purged from the injection equipment shall not be included for payment.

After the injection process has been completed and the epoxy allowed to fully cure, the injection ports and surface seal shall be removed from all surfaces. Ports shall be cut or knocked off, while the surface seal and any spillage shall be ground off flush with the original surface.

Any damage to the concrete due to the Contractor's operations shall be repaired in a manner satisfactory to the Engineer at no additional cost to the Administration.

The cured injected epoxy shall have penetrated a minimum of 90 percent of the visible crack. Acceptance will be based upon drilling cores of the repaired concrete to determine the depth of penetration from representative locations selected by the Engineer. If the penetration is less than 90 percent of the visible crack along the sides of the core, the crack from which the core was taken will be deemed unsatisfactory and will not be included for payment. A minimum of three 4 in. diameter core samples for the full crack depth of the member or area being repaired shall be required for each 100 ft or fraction thereof per job site. The cored holes shall be filled with epoxy grout.

481.04 MEASUREMENT AND PAYMENT. The preparation of cracks, including chipping, cleaning, sealing, installation and removal of injection ports, testing of repairs, repairing of cored holes and for all material, labor, equipment, tools and incidentals necessary to complete the item will be measured and paid for at the Contract unit price per linear foot for the pertinent Epoxy Pressure Injection item.

The epoxy used shall not be included in this item, but will be measured and paid for at the Contract unit price per quart for the pertinent Epoxy Used for Epoxy Pressure Injection item.

APPENDIX B

EXTENT OF DEBONDING FOR EACH RUN

Epoxy	Processing date	Temp	Cycling schedule	Tensile test date	Strength of cycled specimen	Strength of static specimen	Comments
Concresive 1360	3/18-3/25	65F	4 days cycle/3 days static	3/25		28,635 lb 4051 psi	Cyclic displacement = 0.004”. Cycled specimen seemed to have pumped most of the epoxy out of the gap during cycling. The remainder broke during cycling. 3.9% of area showed epoxy fracture (96% showed debond).
Concresive 1360	3/25-4/1	65F	4 days cycle/3 days static	4/1		16,080 lb 2275 psi	Cyclic displacement = 0.003”. Cycled specimen broke before end of 7 days. HPU turned off for some reason allowing X-head to apply its weight to sample. 29% of the surface showed epoxy did not bond to itself, but it did bond to the metal. Note smooth fracture surface in photos of static sample. This is fracture through the epoxy (not a void in the epoxy) because bubble indentations match on both exposed surfaces proving that a crack propagated through the bubbles. Static specimen: 34% of area showed epoxy fracture (66% showed debond).
Eva-Pox Resin 4	4/5-4/12	65F	4 days cycle/3 days static	4/13	550 lb	13,695 lb 1937 psi	Cyclic displacement = 0.003”. Cycled specimen 75% of its surface unbonded to the mating surface. 57% of static specimen had fracture through the epoxy (43% debond)
Eva-Pox Resin 4	6/9-6/16	65F	6 h hold/4 days cycle/66 h static	6/16	12,760 lb 1805 psi	14,700 lb 2212 psi	Static specimen: epoxy did not fill 6% of area. 28% of area showed epoxy fracture. 66% showed debond. Cycled specimen: 31% of area was debond. (69% fracture through epoxy)
Concresive 1360	6/16-6/23	65 F	6 h hold/4 days cycle/66 h static	6/24	22,257 lb 3149 psi	15,772 lb 2231 psi	Cycled specimen: nearly all debond. Static specimen: 34% fracture through epoxy. (66% debond)
Eva-Pox Resin 36	6/24-7/5	65F	6 h hold/4 days cycle/remainder static	8/17	3780 lb 535 psi	4280 lb 605 psi	Cured epoxy is soft and rubbery.

DOE Runs							
Eva-Pox Resin 4	11/29-12/7	68F	39 h hold/4 days cycle/remainder static	12/8	23,070 lb 3264 psi	24,620 lb 3483 psi	Static specimen had 17% debond. Cycled specimen had 100% fracture through epoxy.
Eva-Pox Resin 4	12/8-12/15	45F	39 h hold/4 days cycle/remainder static	12/16	15,480 lb	21,030 lb	HPU was turned off sometime during the cycling. This test not included in DOE.
Eva-Pox Resin 4	12/15-12/22	45F	39 h hold/4 days cycle/remainder static	12/27	15,270 lb 2160 psi	20,220 lb 2861 psi	Static specimen had 16% debond. Cycled specimen had 100% fracture through epoxy.
Eva-Pox Resin 4	12/28-1/4	68F	39 h hold/4 days cycle/remainder static	1/6	22,080 lb 3124 psi	30,300 lb 4287 psi	Static specimen had 7% debond. Cycled specimen had 10% debond.
Eva-Pox Resin 4	1/5-1/12	83F	16 h hold/4 days cycle/remainder static	1/13	19,230 lb 2720 psi	23,680 lb 3350 psi	Static specimen had 44% debond. Cycled specimen had 100% fracture through epoxy.
Eva-Pox Resin 4	1/20-1/27	68F	6 h hold/4 days cycle/remainder static	1/31	340 lb 48 psi	24,050 lb 3402 psi	Static specimen had 20% debond. Cycled specimen had 99% debond or areas where epoxy coated the surfaces but did not bond together.
Eva-Pox Resin 4	1/27-2/3	52F	16 h hold/4 days cycle/remainder static	2/8	17,510 lb 2477 psi	16,940 lb 2397 psi	Epoxy on both fixtures softer than previous runs. Mix ratio was most likely incorrect. Run not included in DOE. Static specimen had 27% debond. Cycled specimen had 100% fracture through epoxy.
Eva-Pox Resin 4	2/7-2/14	68F	39 h hold/4 days cycle/remainder static	2/16	19,140 lb 2708 psi	27,790 lb 3931 psi	Static specimen had 34% debond. Cycled specimen had 100% fracture through epoxy.
Eva-Pox Resin 4	2/15-2/22	90F	39 h hold/4days cycle/remainder static	3/1	18,990 lb 2687 psi	29,570 lb 4183 psi	Static specimen had 61% debond. Cycled specimen had 3% debond.
Eva-Pox Resin 4	2/24-3/3	68F	39 h hold/4days cycle/remainder static	3/7	14,730 lb 2084 psi	27,260 lb 3857 psi	Static specimen had 3.5% debond. Cycled specimen had 100% bond.
Eva-Pox Resin 4	3/7-3/14	83F	62 h hold/4 days cycle/remainder static	3/15	14,540 lb 2057 psi	23,860 lb 3375 psi	Static specimen had 68% debond. Cycled specimen had 0.7% debond.

Eva-Pox Resin 4	3/15-3/22	68F	72 h hold/4 days cycle/remainder static	3/31	17,580 lb 2487 psi	24,240 lb 3429 psi	Static specimen had 19% debond. Cycled specimen had 100% bond.
Eva-Pox Resin 4	3/28-4/4	52F	62 h hold/4 days cycle/remainder static	4/6	14,520 lb 2054 psi	15,880 lb 2247 psi	Static specimen had 24% debond. Cycled specimen had 100% bond.
Eva-Pox Resin 4	4/5-4/12	68F	39 h hold/4 days cycle/remainder static	4/19	14,590 lb 2064 psi	22,480 lb 3180 psi	Static specimen had 18% debond. Cycled specimen had 2% debond.
Eva-Pox Resin 4	4/13-4/20	52F	19 h hold/4 days cycle/remainder static	5/2	19,020 lb 2691 psi	20,430 lb 2890 psi	Target hold time was 16 hours, but cycling started 3 hours later. Test not included DOE.
Eva-Pox Resin 4	4/20-4/27	52F	16 h hold/4 days cycle/remainder static	5/2	17,710 lb 2505 psi	25,100 lb 3551 psi	Static specimen had 14% debond. Cycled specimen had 2 % debond.

APPENDIX C

T-TEST RESULTS

Randomized Run Order	Temperature (^oF)	Hold Time (hours)	Static Bond Strength (psi)	Cycled Bond Strength (psi)
1	68	39	3483	3264
2	45	39	2861	2160
3	68	39	4287	3124
4	83	16	3350	2720
5	68	6	3402	48
6	68	39	3931	2708
7	90	39	4183	2687
8	68	39	3857	2084
9	83	62	3375	2057
10	68	72	3429	2487
11	52	62	2247	2054
12	68	39	3180	2064
13	52	16	3551	2505

t-Test: Two-Sample Assuming Unequal Variances

	Static bond strength	*Cycled bond strength*
Mean	3472	2304.769231
Variance	293772.1667	624218.6923
Observations	13	13
Hypothesized Mean Difference	0	
df	21	
t Stat	4.39247426	
P(T<=t) one-tail	0.000127099	
t Critical one-tail	1.720743512	
P(T<=t) two-tail	0.000254199	
t Critical two-tail	2.079614205	

Randomized run #5 deleted

Randomized Run Order	Temperature (°F)	Hold Time (hours)	Static Bond Strength (psi)	Cycled Bond Strength (psi)
1	68	39	3483	3264
2	45	39	2861	2160
3	68	39	4287	3124
4	83	16	3350	2720
6	68	39	3931	2708
7	90	39	4183	2687
8	68	39	3857	2084
9	83	62	3375	2057
10	68	72	3429	2487
11	52	62	2247	2054
12	68	39	3180	2064
13	52	16	3551	2505

t-Test: Two-Sample Assuming Unequal Variances

	Static bond strength	*Cycled bond strength*
Mean	3477.833333	2492.833333
Variance	319996.1515	179381.7879
Observations	12	12
Hypothesized Mean Difference	0	
df	20	
t Stat	4.828499347	
P(T<=t) one-tail	5.10275E-05	
t Critical one-tail	1.724718004	
P(T<=t) two-tail	0.000102055	
t Critical two-tail	2.085962478	