Report to Warren Environmental

Hydrostatic Pressure Tests of Spray-Applied Epoxy Lining System

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EXECUTIVE SUMMARY

An experimental program intended to assess the ability of spray-applied S-301 epoxy to resist hydrostatic pressure was carried out. The hydrostatic pressure was applied through a tap embedded in a concrete substrate resulting in the pressure being resisted essentially by the epoxy application alone. The intent was to mimic hydrostatic forces driving infiltration into a cracked concrete pipe repaired with the S-301 material. The hydrostatic pressure results from the pipe being buried below the water table.

Specimens were prepared from concrete having a measured compressive strength of 5075 psi and an approximate direct tensile strength of 285 psi. Initial flaws resembling spalls or pop-outs ranging from 0.5 to over 6 in. in diameter were created in the concrete specimens. The epoxy applications varied in specified thickness from 0.125 to 0.75 in. Some specimens included filling the initial flaws with M-301 mastic although most did not. Most specimens had epoxy applied in a saturated-surface dry condition while some had standing water present during application. Every effort was made to mimic the materials and surfaces typical of a large diameter concrete pipe application.

The following conclusions were drawn:

1. The average ultimate capacity of all specimens exceeds 400 psi hydrostatic pressure – this is equivalent to a hydrostatic head of 920 feet. The standard deviation over all specimens was about 80 psi (20%); the low value was 250 psi and the high was 650 psi.
2. A marginal increase in capacity was observed for specimens having thinner epoxy thickness although little significant effect on ultimate capacity was observed for epoxy thickness up to 0.75 in.
3. Initial flaw size, up to about 4 in. diameter, had no effect on ultimate capacity, although larger flaw sizes did lead to larger variation of results.
4. Larger flaws (in a few cases exceeding 6 in. diameter) first repaired with M-301 mastic behaved marginally better than those in which the epoxy was simply sprayed over the flaw.
5. No significant difference in ultimate capacities was observed between those specimens sprayed in the saturated-surface dry condition and those in which standing water was present, although the wet specimens did exhibit greater variability.
6. Test specimens subject to approximately 125 psi for sustained periods up to 115 hours and then tested to failure exhibited no difference in behaviour from those not subject to sustained hydrostatic pressure.

In general, the observed failures are characterised by the water under hydrostatic pressure initiating and propagating a crack from the tap (crack in concrete) through the concrete layer immediately adjacent the epoxy. This forms a 'bubble' of pressurized water which the epoxy is resisting. As the delaminated bubble grows radially from the tap, the force causing delamination (a function of the area of delamination) increases faster than the circumference of the delamination (were resistance to failure is mobilised). Failure occurs when the epoxy delamination fails in shear around the circumference of the delamination. A simple mechanical approach to evaluating the hydrostatic test behaviour and failure suggests that the S-301 epoxy has a shear capacity of approximately 2700 psi. Additional calculations show that a flexural failure (tension at the outer face) of the epoxy 'bubble' is unlikely since the flexural stresses at shear failure are approximately five times less than the reported material capacity in this regard.

Standard ASTM D7522 pull-off tests were conducted on slabs following hydrostatic testing. The following conclusions were drawn:

7. Apparent pull-off strength is inversely proportional to epoxy thickness. It is hypothesized that the predrilling operation weakens the interface since for a thicker epoxy, a larger ‘plug’ of epoxy is contained in the core barrel. This core barrel is not friction-free, in which case the large plug results in larger torsional forces (shear) affecting the interface prior to pull-off testing.

8. Specimens having epoxy thickness up to 0.500 in. exhibited pull-off tests results essentially capturing the concrete tensile strength. Thicker applications were apparently weaker, lending support to the hypothesis put forth in the previous conclusion.

9. Generally, the *in situ* epoxy thickness was greater than the specified thickness.

This report clearly demonstrates that the S-301 epoxy applied directly to a concrete substrate is adequate to resist hydrostatic infiltration pressure of 100 psi with a factor of safety of approximately 4.

SPRAY-APPLIED EPOXY PIPE LINING SYSTEMS

A spray lining system is intended to be applied to the inside of a concrete pipe, sealing the pipe and mitigating limit states associated with infiltration (or exfiltration). The resulting lining is a thin, durable, chemical resistant product that is intimately and permanently bonded to the host pipe. The lining serves to provide *continuity* to the inner surface of the pipe; it bridges existing and anticipated cracks in the concrete host pipe, preventing infiltration products from completely penetrating the pipe. The epoxy thickness is primarily a function of the amplitude of the concrete substrate to which it is applied. The epoxy serves to 'fill' the small amplitude variation present on the prepared substrate and may be built out beyond this to provide a smooth interior finish as necessary. Considerations of impact and/or abrasion resistance may also inform the design thickness of the epoxy lining.

The liner is intimately bonded to the concrete substrate and relies on this bond to provide the required performance. Large regions of debonding are unlikely and may be immediately addressed upon initial inspection following installation.

Small regions of infiltration pressure reaching the depth of the liner through existing or anticipated cracks in the host pipe are likely. These are resisted by the bridging action of the epoxy layer. This is a design consideration unique to such systems and is described in the following section.

Because the lining offers little structural enhancement in large diameter elements, the host pipe must be able to resist all mechanical and hydrostatic loads. If the host concrete pipe is shown to be structurally adequate, the epoxy lining is required only to address the infiltration limit states.

Local Hydrostatic Pressure

In systems having adequate host pipe structural capacity, the lining is only required to address the infiltration limit state. For this, intimate bond between the epoxy and substrate concrete is required. Quality control can ensure the integrity of this bond at the time of and shortly following installation.

Nonetheless, future cracking of the concrete host pipe must be anticipated. Such cracking will permit ground water to infiltrate the concrete pipe and should be expected to result in *local* spikes in hydrostatic pressure at the locations of the cracks. Elongation properties of the epoxy (rupture strains of 0.048 are reported for the epoxy considered in this study) are at least two orders of magnitude greater than the concrete cracking strain, thus the epoxy should bridge the cracks with relative ease.

Conceptually, the epoxy bond must be sufficiently robust to resist the 'wedging' or 'prying' action of the hydrostatic pressure, p at the concrete-epoxy interface. A simple analogue is shown in Figure 1a, representing a section through a crack having a crack width of w. At each side of the crack, the hydrostatic pressure results in:

1. a tensile force, σ_2, generated in the epoxy which is transferred to the concrete through Mode II shear stresses, τ_2; and;
2. a Mode I tensile force acting at the epoxy-concrete interface at the edge of the crack resisting the hydrostatic force $pw/2$.

These forces result in a complex 'mixed mode' stress condition at the epoxy-concrete interface as shown in Figure 1b. Two failure planes may result:

A: adhesive failure along the interface (Figures 1a and 1b). This failure path is associated with the *in situ* bond strength of the epoxy.

B: cohesive failure in the concrete adjacent the epoxy interface (Figures 1a and 1c). This failure path is associated with the concrete tensile properties.

Experience with epoxy adhesives bonded to concrete indicates that the adhesive bond strength far exceeds the concrete tensile strength; therefore path **B** is more likely. The mixed mode nature of loading (Figure 1c), the *in situ* compressive circumferential stresses resulting from the thick-walled cylinder behaviour of the host pipe, the anticipated tortuous failure path, and additional uncertainties make calculation and/or prediction of this failure mode virtually impossible. For this reason, an experimental study is undertaken to establish empirical behaviour parameters.

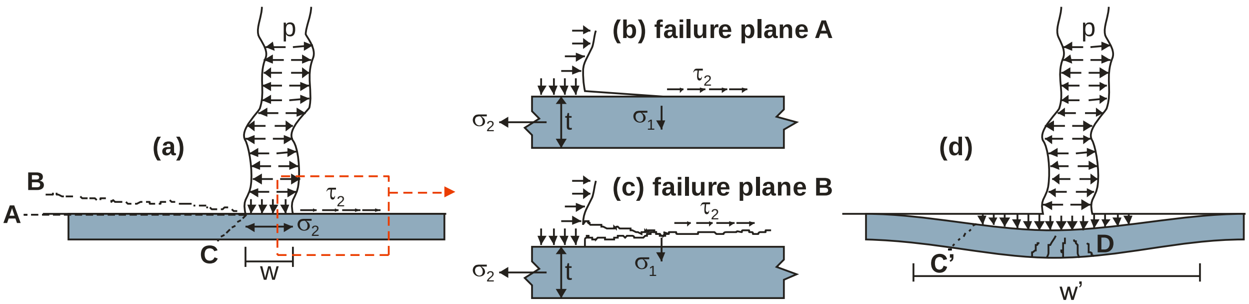


Figure 1 *Conceptual* representation of debonding phenomena.

A third failure mode: **C**: punching shear of the epoxy layer, is more easily addressed by ensuring that the shear capacity of the epoxy layer (f_{ev}) is sufficient to resist the punching shear force with an appropriate factor of safety (N_{pv}).

$$f_{ev}/N_{pv} \geq pw/4t$$

This equation is based on the idealized conceptual treatment of problem shown in Figure 1a and assumes a circular failure surface having a diameter *w*. The shear capacity may be justifiably increased by a factor of $\sqrt{2}$, recognising the typical 45^{o} inclination of the shear failure plane.

Assuming failure initiates, the epoxy (with some substrate concrete attached) will begin to debond/delaminate and the region under pressure will become larger (see Figure 1d for conceptual representation). This will generally be a self-arresting behaviour since as the affected region becomes larger, more concrete is engaged while *p* does not increase. Thus there is a critical flaw dimension, *w'* beyond which the delamination will not propagate. However, the relatively thin epoxy layer is now a membrane, spanning *w'* and supporting the pressure *p*. Thus the epoxy may fail in **C'**: shear:

$$f_{ev}/N_{pv} \geq pw'/4t$$

Failure may also occur in **D**: flexure (governed by the epoxy modulus of rupture, f_{er}). In this case the failure will be affected by the rotational stiffness of the epoxy (primarily a function of thickness, t). Assuming a flexible epoxy yields the largest flexural stress (Roark's 3[e], Table 24, Case 10a) and therefore the critical case:

$$f_{er}/N_{pt} \geq 6pw'^{2}(3+v)/64t^{2}$$

These equations are based on an ideal circular flaw of diameter *w'* shown in Figure 1d. *v* is Poisson's ratio of the epoxy, often assumed to be 0.3.

EXPERIMENTAL PROGRAM

The experimental program is intended to replicate 'blow out' failures under hydrostatic pressure. A schematic representation of the 4 in. thick concrete slab specimens is shown in Figure 2. Experimental parameters include:

1. Initial flaw size, *w*. The initial flaws are created by varying the depth of embedment of the pressure tap cover, *c* and then 'knocking' out the cover concrete through the pressure tap. This results in a relatively natural concrete failure surface as shown in Figure 3.
2. Epoxy thickness, *t*
3. Surface preparation/condition prior to epoxy installation (amplitude, saturation, etc.)
4. Filler in flaw (epoxy only, epoxy mastic, bond breaking material modelling deteriorated concrete)

The test protocols involve providing hydrostatic pressure, *p*, through the pressure pipe as follows:

1. Monotonic increase of pressure to failure in order to establish failure loads and to identify the critical limits states.
2. 'Proof' pressure maintained for long duration to establish creep behaviour.

Test Specimens

Each 4 in. thick concrete slab is 22 x 36 in. in plan (Figure 2b) and has six pressure taps located on a 12 inch grid. Each slab has the same combination of experimental parameters, particularly epoxy thickness; thus six repetitions of each test are performed. Each slab also permits four locations for direct tension tests performed in accordance with ASTM D7522. Data from the direct tension tests will be correlated with hydrostatic test performance. This is important since direct tension is the most likely method of quality assurance in the field.

The test matrix is provided in Table 1. In this matrix, t = 0.500 in. with c = 0.25 and $w \approx 1.5$ in. serves as the 'control' case. The actual values of *t* and *w* are reported for each test in Appendix A.

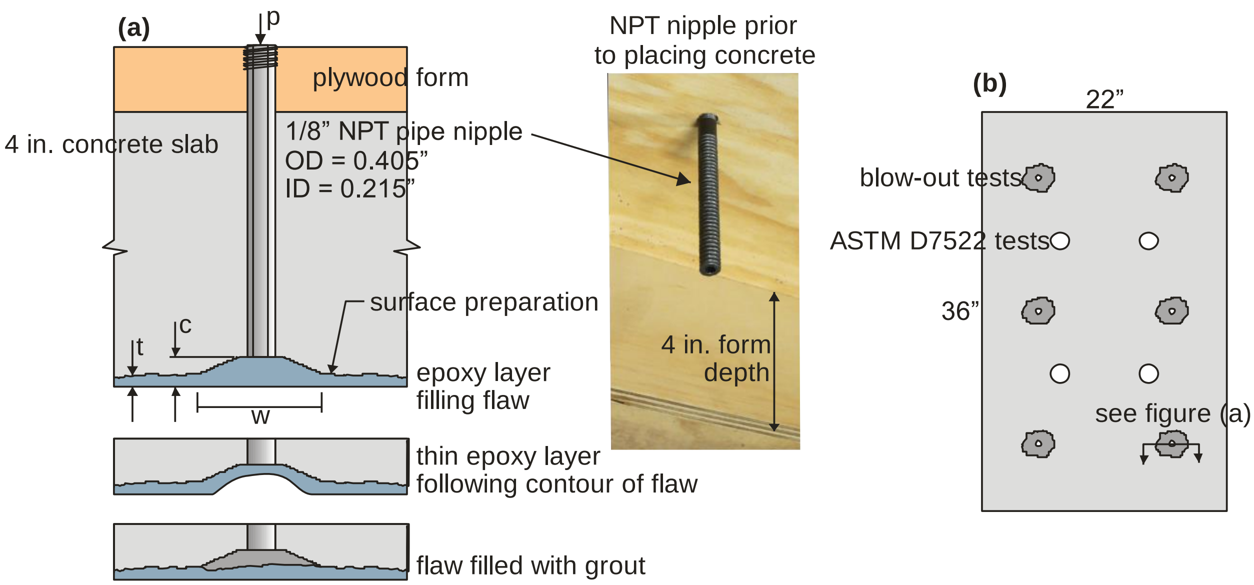


Figure 2 Test specimens.

Table 1 Test matrix.

load protocol	Slab ID	t in.	c in.	w in.	surface prep	filler	Notes
monotonic load to failure	500-15-1	0.500	0.25	≈1.5	SSD	none	control specimens
	500-15-2	0.500	0.25	≈1.5	SSD	none	
	500-15-3	0.500	0.25	≈1.5	SSD	none	
	125-15	0.125	0.25	≈1.5	SSD	none	vary *t*
	250-15	0.250	0.25	≈1.5	SSD	none	
	375-15	0.375	0.25	≈1.5	SSD	none	
	625-15	0.625	0.25	≈1.5	SSD	none	
	750-15	0.750	0.25	≈1.5	SSD	none	
	500-05	0.500	0.05	≈0.5	SSD	none	vary *w*
	500-25	0.500	0.50	≈2.5	SSD	none	
	500-15-W1	0.500	0.25	≈1.5	wet	none	vary surface condition
	500-15-W2	0.500	0.25	≈1.5	wet	none	
	500-15-G	0.500	0.25	≈1.5	SSD	mastic	vary filler
	500-25-G	0.500	0.50	≈2.5	SSD	mastic	
	500-40-G	0.500	0.95	> 4.0	SSD	mastic	
	500-15-V	0.500	0.25	≈1.5	SSD	void	
	500-25-V	0.500	0.50	≈2.5	SSD	void	
	500-40-V	0.500	0.95	>4.0	SSD	void	
creep test	500-15-C1	0.500	0.25	≈1.5	SSD	none	
	500-15-C2	0.500	0.25	≈1.5	SSD	none	

Surface Preparation:
SSD = saturated surface dry
wet = standing water

Filler:
none = epoxy follows contour of flaw
mastic = flaw repaired with epoxy mastic
void = flaw filled with foam in order to mimic the presence of a larger initial void

Material Properties

Concrete

Ready mix concrete having maximum aggregate size of 0.5 in. and specified compression strength of 4000 psi was used to cast all specimens. Measured concrete compression strength (f_c per ASTM C39), split cylinder tension strength (f_{sp} per ASTM C496) and modulus of rupture (f_r per ASTM C78) are given in Table 2. All cylinders were standard 4 in. diameter cylinders and the modulus of rupture specimens were standard 6 in. beams. Test results indicate that the 28 day concrete compressive strength was f_c' = 5075 psi. Variation of all material test data fell well within acceptable and expected limits.

Table 2 Measured concrete material properties.

age (days)	specimens cast 10 Dec. 2012	ASTM C39 compression tests			ASTM C496 split cylinder tests			ASTM C78 modulus of rupture		
		n	f_c (psi)	COV	n	f_{sp} (psi)	COV	n	f_r (psi)	COV
28	7 Jan. 2013	3	f_c' = 5075	0.079	-	-	-	3	501 $7\sqrt{f_c'}$	0.036
66	epoxy applied 14 Feb. 2013	3	5287	0.023	-	-	-	-	-	-
86	hydrostatic tests 4 – 7 Mar. 2013	-	-[1]	-	3	384 $5.4\sqrt{f_c'}$	0.143	3	716 $10\sqrt{f_c'}$	0.022

[1] data unavailable due to test error

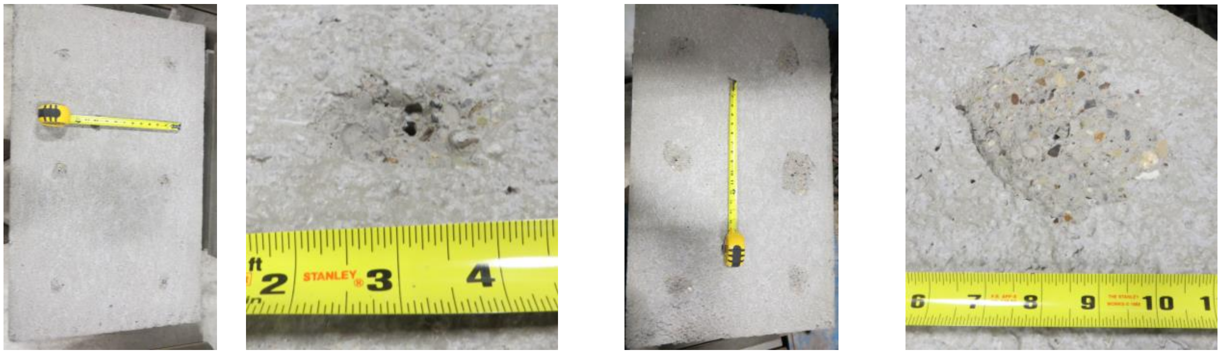
A rule of thumb is that the direct tension capacity of concrete is approximately $0.70f_{sp}$ and $0.50f_r$. Therefore the direct tension capacity of the concrete in the test specimens is on the order of 270 - 350 psi ($3.8\sqrt{f_c'} – 4.9\sqrt{f_c'}$). In the absence of test results, direct tension strength is typically given as $4\sqrt{f_c'}$, in this case, 285 psi.

Epoxy

Warren S-301 Epoxy was used for all tests. The manufacturer's material data sheet is included in Appendix B. Warren is the sponsor of this investigation and no specific material tests were conducted on the epoxy used.

Flaw Creation

The flaws were created by inserting a flat-bottomed probe through the embedded pipe nipple and 'knocking' the cover concrete out, creating the flaw. In general, the flaws created were 'craters' having a depth *c* and sides inclined at a shallow angle of about 30^o (shown schematically in Figure 2). Images of typical flaws are provided in Figure 3. The size of each flaw as it is expressed at the concrete surface was measured in the directions parallel to the slab slides. This data is presented in Appendix A.



a) c = 0.25; $w \approx 1.5$　　　　b) c = 0.50; $w \approx 2.5$

Figure 3 Representative examples of flaws.

Surface Preparation

Surface preparation was conducted by A&W Maintenance technicians. Preparation consisted of washing the slab surface with 1.5% muriatic acid solution followed by pressure washing with water at 5500 psi to remove laitance and the very top layer of mortar paste. The resulting slab surface was qualitatively assessed to range from CSP6 to CSP8 using ICRI concrete surface profile (CSP) chips. The slabs (with the exception of 500-15-W1 and W2) were surface dried using a leaf blower resulting in a 'saturated surface dry' (SSD) condition at the concrete-epoxy interface. Figure 4a shows the general condition of the slab surfaces prior to epoxy application.

Filling of Flaws

While most specimens received epoxy as is, three slabs, labelled 500-xx-G, had their flaws filled with Warren M-301 trowel-on epoxy mastic (see Appendix B for material data sheet) prior to spray application. The mastic was trowel-finished flush with the existing concrete surface and had the same basic profile as the surrounding surface. Figure 4b shows a mastic-filled flaw.

Three additional slabs, labelled 500-xx-V, had a spray-foam[1] plug placed in their flaws prior to epoxy application. The plug was finished flush with the concrete surface and is intended to represent a larger flaw or a flaw at which the epoxy has experienced some degree of debonding. The foam plug does not permit the epoxy to bond to the flaw surface and also results in a larger 'pocket' behind the epoxy subject to hydrostatic pressure. Figure 4c shows a foam filled flaw.

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[1] *Dow "Great Stuff" Window and Door Sealant*

a) surface condition following preparation (CSP8 shown) | b) mastic-filled flaw | c) foam-filled flaw

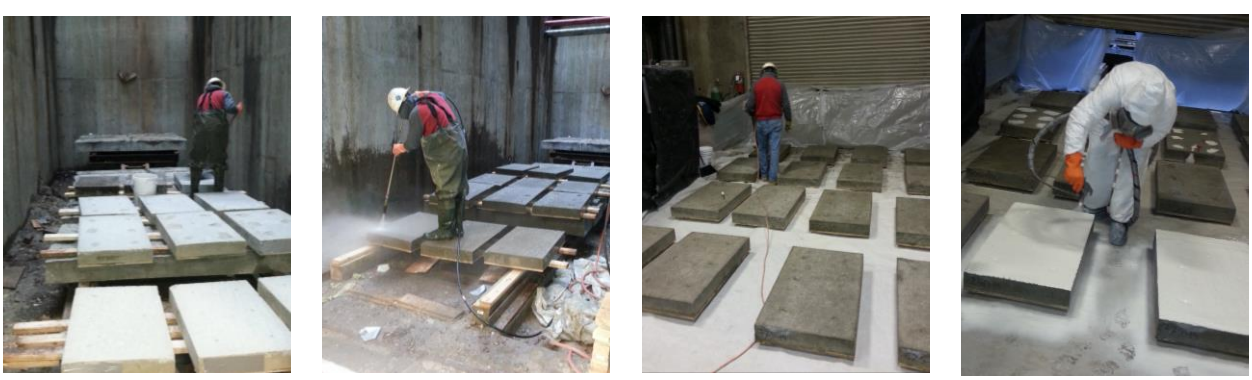
Figure 4 Representative surface and flaw preparation.

Surface Condition at Epoxy Application

The surface condition at the time of epoxy application of all specimens except 500-15-W was ‘saturated surface dry” (SSD). Specimens 500-15-W1 and W2 were sprayed with water immediately prior to epoxy application such that there was a small amount of standing water in the indentations of the concrete surface..

Epoxy Application

Warren S-301 Epoxy was applied by A&W Maintenance technicians on 14 February 2013; the concrete slabs were 66 days old at this time. Specimens having epoxy thicknesses of 0.125, 0.25 and 0.375 in. (i.e those labelled 125-15, 250-15 and 375-15) were applied in a single coat. All 500-xx specimens had two equal lifts of 0.25 in. each. Specimens 675-15 and 750-15 had initial coats of 0.375 in. and a second coat of 0.25 and 0.375 in., respectively. For all cases with a second coat, this was placed approximately 3 hours and 45 minutes after the first. Ambient conditions during the entire spraying and initial curing were an interior laboratory environment with the temperature approximately 59^{o}F and relative humidity approximately 70%.



a) wash with 1.5% muriatic acid | b) high pressure (5500 psi) water wash | c) surface dry specimens | d) spray application of epoxy

Figure 5 Epoxy application.

HYDROSTATIC TEST PROGRAM

Test Method

Hydrostatic testing was conducted the week of 4 March, 2013. The concrete at this time was 84 days old and the epoxy had cured 18 days. Hydrostatic pressure was applied through the embedded pipe nipples (Figure 2). Each flaw was tested individually using a *Wheeler-Rex* Hydrostatic Test Pump having a capacity of 1000 psi. A 1000 psi digital pressure gauge was used to record the maximum pressure prior to failure of each test. Deflection of the epoxy immediately above the flaw was monitored in some specimens using a 0.0001 inch precision dial gauge. The test apparatus, typical of that used to test pressurized pipe systems, is shown in Figure 6.

Hydrostatic tests yielded two values of pressure. The 'cracking' pressure is the pressure at which the initial cracking of the concrete in the immediate vicinity of the pressure tap appears to occur. This results in the formation of an annular space and an instantaneous (although recoverable) drop in test hydrostatic pressure. As more water is pumped in, the pressure drop is recovered and a further increase in pressure is observed as the annular space is enlarged in an essentially radial manner. The 'ultimate' pressure is the highest pressure recorded in the test, typically occurring immediately before failure. Following failure, the epoxy is 'sounded' to determine the extent of the annular space formed in each test. Determination of the cracking pressure is based on operator sensitivity to the progression of the test and is very often difficult to identify; for this reason fewer cracking pressures are reported. A summary of cracking and peak pressures attained is provided in Table 3 and data for each test is provided in Appendix A. Views of representative failures are shown in Figure 7.

Failures of one tap often affected performance of subsequent tests on the same slab. It was observed that in some cases, the delamination regions overlapped from test to test (Type III failure, see below). Additionally, where delaminations were larger than anticipated, some taps were not tested in order to ensure sound locations for subsequent pull-off tests. For these reasons, not all specimens have six values associated with ultimate pressure. In future tests, taps should be spaced more widely from the specimen edges and each other.

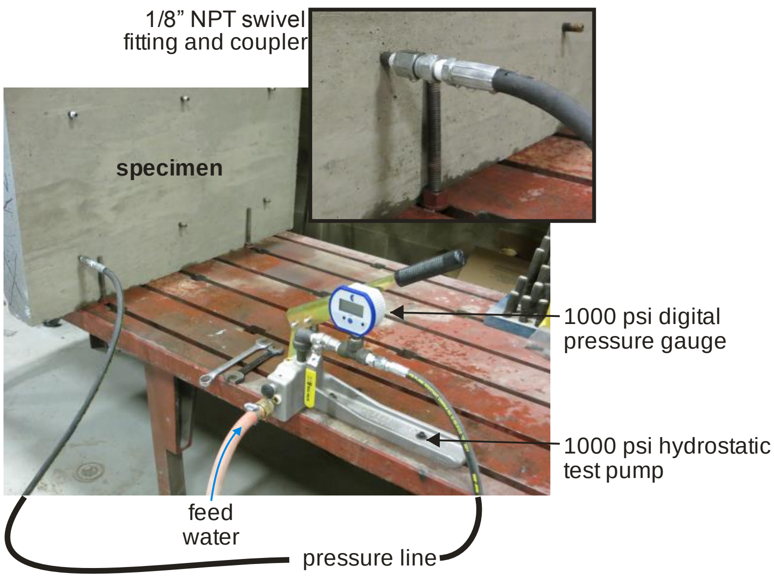


Figure 6 Hydrostatic test apparatus.

Table 3 Summary of hydrostatic pressure test results.

Slab ID	n	average 'cracking' pressure	COV	n	average ultimate pressure	COV
		psi			psi	
500-15-1 & 3	6	250	0.182	9	387	0.157
125-15	2	230	0.184	5	396	0.119
250-15	3	233	0.131	5	392	0.261
375-15	1	240	-	5	474	0.239
625-15	3	240	0.240	5	358	0.183
750-15	1	220	-	5	396	0.160
500-05	4	270	0.109	6	385	0.075
500-25	2	280	0.202	4	388	0.464
500-15-W1 & W2	7	277	0.431	9	398	0.186
500-15-G	2	200	0.071	6	383	0.179
500-25-G	1	300	-	6	445	0.135
500-40-G	4	270	0.174	6	443	0.264
500-15-V	1	260	-	6	273	0.176
500-25-V	0	-	-	5	120	0.177
500-40-V	0	-	-	6	88	0.301

Considering only hydrostatic pressure results shown in Table 3, the following conclusions are drawn; these conclusions exclude the 500-xx-V specimens which are discussed in conclusion 6.

1. The average ultimate capacity of all specimens exceeds 400 psi hydrostatic pressure – this is equivalent to a hydrostatic head of 920 feet. The standard deviation over all specimens was about 80 psi (20%); the low value was 250 psi and the high was 650 psi.

2. A marginal increase in capacity was observed for specimens having thinner epoxy thickness (Figure 7a); this increase may reflect the 'size effect' with thinner epoxy layers being more consistent and having fewer flaws. No significant effect on ultimate capacity was observed for epoxy thickness up to 750 mil.

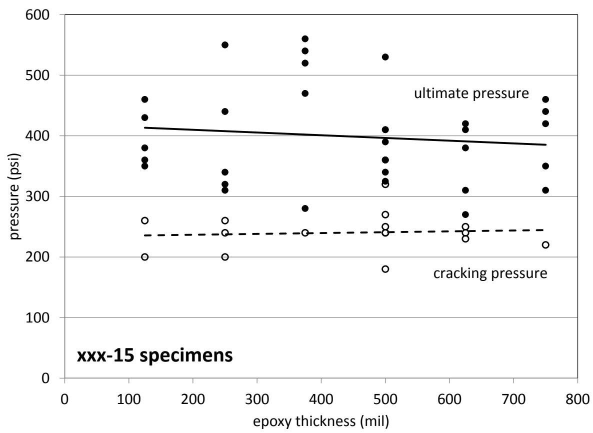
3. Initial flaw size, up to about 4 in. diameter, had no effect on ultimate capacity, although larger flaw sizes did lead to larger variation of results (Figure 7b).

4. Larger flaws (in a few cases exceeding 6 in. diameter) first repaired with M-301 mastic behaved marginally better than those in which the epoxy was simply sprayed over the flaw (Figure 7b).

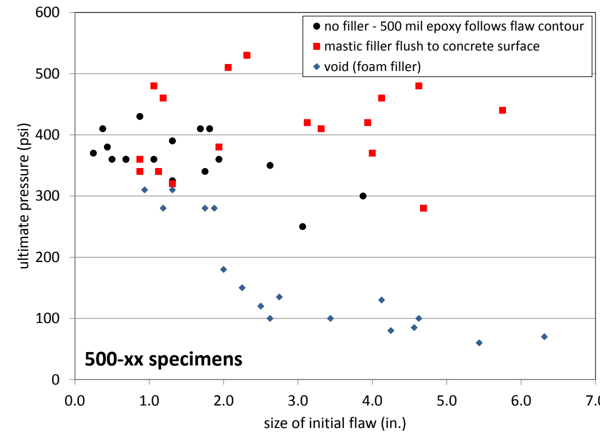
5. No significant difference in ultimate capacities was observed between those specimens sprayed in the saturated-surface dry condition (SSD) and those in which standing water (wet) was present, although the wet specimens did exhibit greater variability (Figure 7c).

6. The specimens having an initial void (500-xx-V) created using spray foam behaved quite poorly and the behaviour degraded with increased flaw size (Figure 7b). During epoxy application some reaction between epoxy and foam, manifest by off-gassing, was observed; the epoxy discoloured in all regions above the foam filler and remained discoloured. It is hypothesized that the foam and epoxy reacted

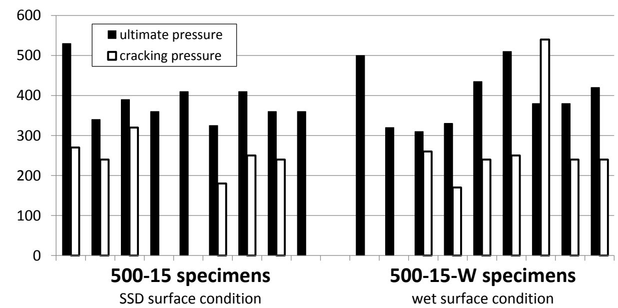
with each other, degrading the epoxy. Forensic examination of the epoxy overlying the foam revealed no obvious flaws. An SEM evaluation may reveal the issue but is well beyond the scope of this work.



a) pressure versus epoxy thickness



b) pressure versus flaw size and preparation



c) pressure versus surface condition at epoxy application

Figure 7 Hydrostatic test results.

Failure Modes Observed

The following failure modes were observed. These are identified for each test in Appendix A. Representative images of these failures are shown in Figure 8.

Failure Type I: *Punching Shear Failure of Epoxy*. This failure is believed to be most typical of *in situ* applications where there are no specimen edges. The hydrostatic pressure cracks the concrete in the vicinity of the flaw and water fills in behind the sound epoxy. With increasing pressure, the crack propagates essentially radially from the flaw as shown schematically in Figure 1c along a plane **B** through the concrete immediately adjacent the epoxy. This is a cohesive failure in the substrate concrete. The force behind the epoxy delamination builds with the square of the delamination diameter (area), w' in Figure 1d, while the resistance of the epoxy is a function of only the diameter (circumference). Thus, eventually, the force behind the epoxy delamination exceeds the shear capacity of the epoxy and a punching failure occurs. This is shown schematically as **C'** in Figure 1d. An example of a Type I punching failure is shown in Figure 8a.

Failure Type II: Delamination Limited by Specimen Edge. This failure mode is the same as Type I, although as the delamination diameter, w', grows, it reaches the edge of the slab – a radial distance of w'/2 = 5 or 5.5 inches before a punching failure occurs. This failure represents a limitation of the specimen geometry. In future tests, taps should be placed further from the edges of the slabs and each other. Nonetheless, based on the results observed, Type II failures clearly were approaching the ultimate punching capacity of the specimens and certainly represent sound proof loads. The epoxy shear capacity calculated based on these is a lower-bound value; i.e.: the *in situ* shear capacity of the epoxy exceeds that calculated based on a Type II failure. Representative Type II failures are shown in Figure 8b.

There were a number of instances where Type I and II failures were observed in combination. This is partially an indication that the punching capacity was being reached at the same value of w’ as resulted in the delamination expressing itself at the slab edge.

Failure Type III: Failure Through or Affected by Other Tap. Similar to Type II failures, interaction with delaminated regions from previous tests results in loss of hydrostatic pressure and the end of a test.

Failure Type IV: Blow Out. In this failure, no delamination is noted surrounding the flaw; the hydrostatic pressure simply blows out a small hole in the epoxy. This is represented schematically by **C** in Figure 1a. This failure was only observed in one specimen (500-40-V-E) and is shown in Figure 8d.

Failure Type V: Blow Back: This failure is indicative of poor concrete consolidation around the embedded pressure tap. In a single test (375-15-A), water pressure was forced back along the tap embedment and was relieved by blowing out the back of the slab around the perimeter of the tap.

a) Type I punching shear failure

b) Type II failures with delamination expressed at edge of specimen.

c) combination of Type I and II failure where punching is observed propagating from location where delamination is expressed at specimen edge.

d) Type IV blow out failure.

Figure 8 Representative failures observed in hydrostatic pressure tests.

Creep Tests

Creep tests were performed on 500-15-C specimens. These tests were conducted using the Benedum Hall sub-basement water supply and a precision regulator to control the pressure. The ‘ambient’ building water pressure is 140 psi; therefore tests could be conducted at any pressure less than this. The test arrangement is the same as shown in Figure 6, except that the feed water is simply allowed through the pump (so that pressure gauge may be used). Constant hydrostatic pressure is established at a flaw and the deflection of the epoxy immediately above the flaw is monitored using a 0.0001 inch precision dial gauge. "Initial deflection" is that (if any) measured immediately following pressurizing the pipe nipple and "final deflection" is that measured at the end of the test duration. Following the creep tests, a hydrostatic test was conducted to failure to determine if the sustained creep loading had any effect on the coating performance. Test parameters and results are given in Table 4.

Three tests were conducted at the highest sustainable pressure of about 126 psi. These showed essentially no signs of distress in which case further creep tests at lower pressures were deemed unnecessary. The average ultimate pressure achieved by the three creep tests was 400 psi. This compares well with the 420 psi result for the single test on the same slab not previously subject to sustained pressure and to the average for all 500-15 specimens of 387 psi. (Table 3). Essentially, no effects relating to maintaining a sustained pressure in excess of 125 psi for as long as 115 hours were observed.

Table 4 Hydrostatic creep test results.

Test ID	creep test				subsequent hydrostatic test ultimate pressure
	hydrostatic pressure	test duration	initial deflection	final deflection	
	psi	h	in.	in.	psi
500-15-C2-F	126	96	0	0.0019	360
500-15-C2-C	126	48	0	0.0018	450
500-15-C2-B	128	115	0	0.0010	390
500-15-C2-E	-	-	-	-	420

PULL-OFF TEST PROGRAM

Standard ASTM D7522 pull-off tests were conducted on slabs following hydrostatic testing. A *Dyna Z-15* test apparatus was used for this test as shown in Figure 9. Since the tests were conducted away from the flaw sites only epoxy thickness (*t*) and surface preparation are variables for these tests. The saw-cut used to isolate the test specimen (ASTM D7522) was extended 0.25 in. into the substrate concrete for all tests. A summary of pull-off strengths attained is provided in Table 5 and data for each test is provided in Appendix A. All observed failures were in the concrete substrate immediately below the epoxy application. Failures involved both fracture of aggregate and separation of aggregate from cement paste in approximately equal proportions. Views of representative failures are shown in Figure 10.

The pull-off tests also permitted accurate measurement of epoxy thickness. This is also shown in Table 5.

Figure 9 *Dyna Z-15* pull-off test apparatus.

Table 5 Summary of ASTM D7522 pull-off test results.

Slab ID	n	average pull-off strength	COV	observed epoxy thickness	COV	observed / specified
		psi		in.		
500-15	6	284	0.214	0.493	0.177	0.99
125-15	3	306	0.297	0.283	0.305	2.26
250-15	3	310	0.281	0.369	0.066	1.48
375-15	3	253	0.457	0.400	0.052	1.07
625-15	3	155	0.287	0.723	0.052	1.16
750-15	3	135	0.108	0.858	0.057	1.14
500-15-W	4	266	0.059	0.497	0.079	0.99

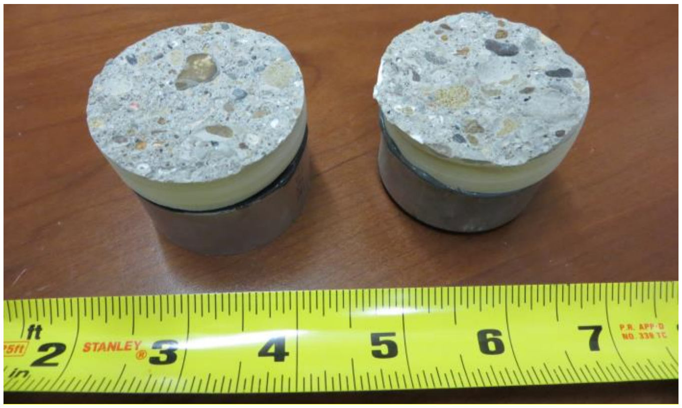


Figure 10 Representative failures observed in pull-off tests (500-15).

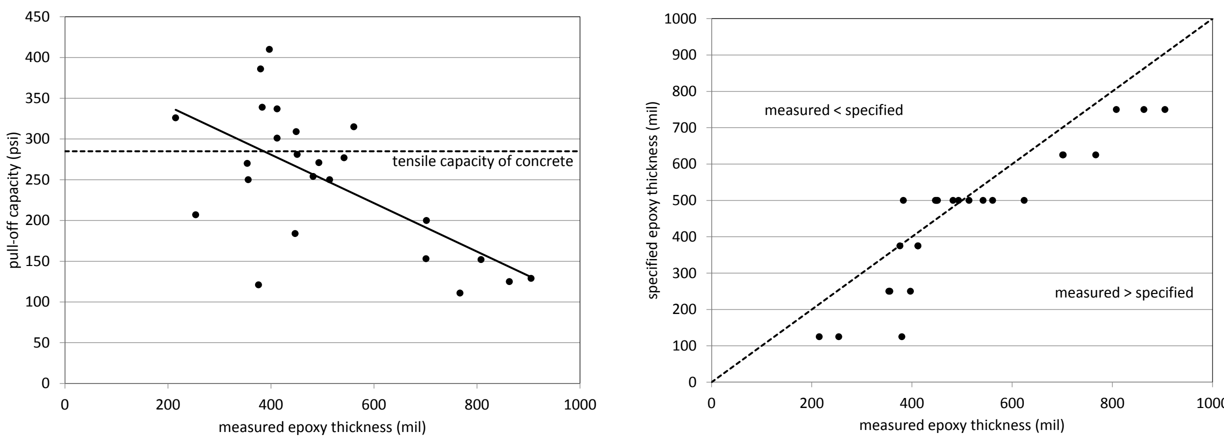
Considering only the pull-off test results shown in Table 5, the following conclusions are drawn:

10. Although highly variable, apparent pull-off strength is inversely proportional to epoxy thickness. There is no sound mechanical basis for this observation since the pull-off test involves affixing a very

stiff disk to the epoxy, negating any effect of the epoxy flexural stiffness. It is hypothesized that the predrilling operation weakens the interface since for a thicker epoxy, a larger 'plug' of epoxy is contained in the core barrel. This core barrel is not friction-free, in which case the large plug results in larger torsional forces (shear) affecting the interface prior to pull-off testing. The trend of epoxy thickness and pull-off capacity is evident in Figure 11a. The relatively large variability may result from the fact that the pull-off tests were conducted on slabs following hydrostatic tests – damage from the latter may have affected the former.

11. The assumed concrete tensile strength is approximately 285 psi. The pull-off tests are not expected to exceed this value. Considering variability, specimens having epoxy thickness up to 0.500 inches exhibited pull-off tests results essentially capturing the concrete tensile strength. Thicker applications were apparently weaker, lending support to the hypothesis put forth in the previous conclusion.

12. Generally, the *in situ* epoxy thickness was greater than the specified thickness as shown in Figure 11b. With the exception of the very thin 0.125 in. epoxy application, the variation in thickness was relatively small and the average ratio by which the *in situ* thickness exceeded the specified is shown in Table 5.



a) pull-off capacity versus epoxy thickness b) measured versus specified epoxy thickness

Figure 11 Pull-off test results.

EPOXY PERFORMANCE

It is informative to discuss the observed data in the context of the mechanics of the problem as described by Figure 1 and in terms of the reported epoxy material properties.

Failure Type and Specimen Size

As noted in the discussions of failure types II and III, the slab specimens were too small to capture the likely ultimate behaviour of the epoxy in most cases. Edge effects and interaction with previously tested regions affected the results. Therefore, while these failures may be used to establish proof loads, only failure type I (and mixed type I-II) may be used to investigate the epoxy behaviour itself without introducing other parameters. Specimens having an initial void (500-xx-V) are also excluded for reasons described in conclusion 6. Table 6 summarises the 18 hydrostatic tests exhibiting type I failures. The remaining discussion considers only these test results.

Epoxy Shear

Type I failures correspond to failure surface **C'** shown in Figure 1. The shear stress carried by the epoxy at failure is calculated as:

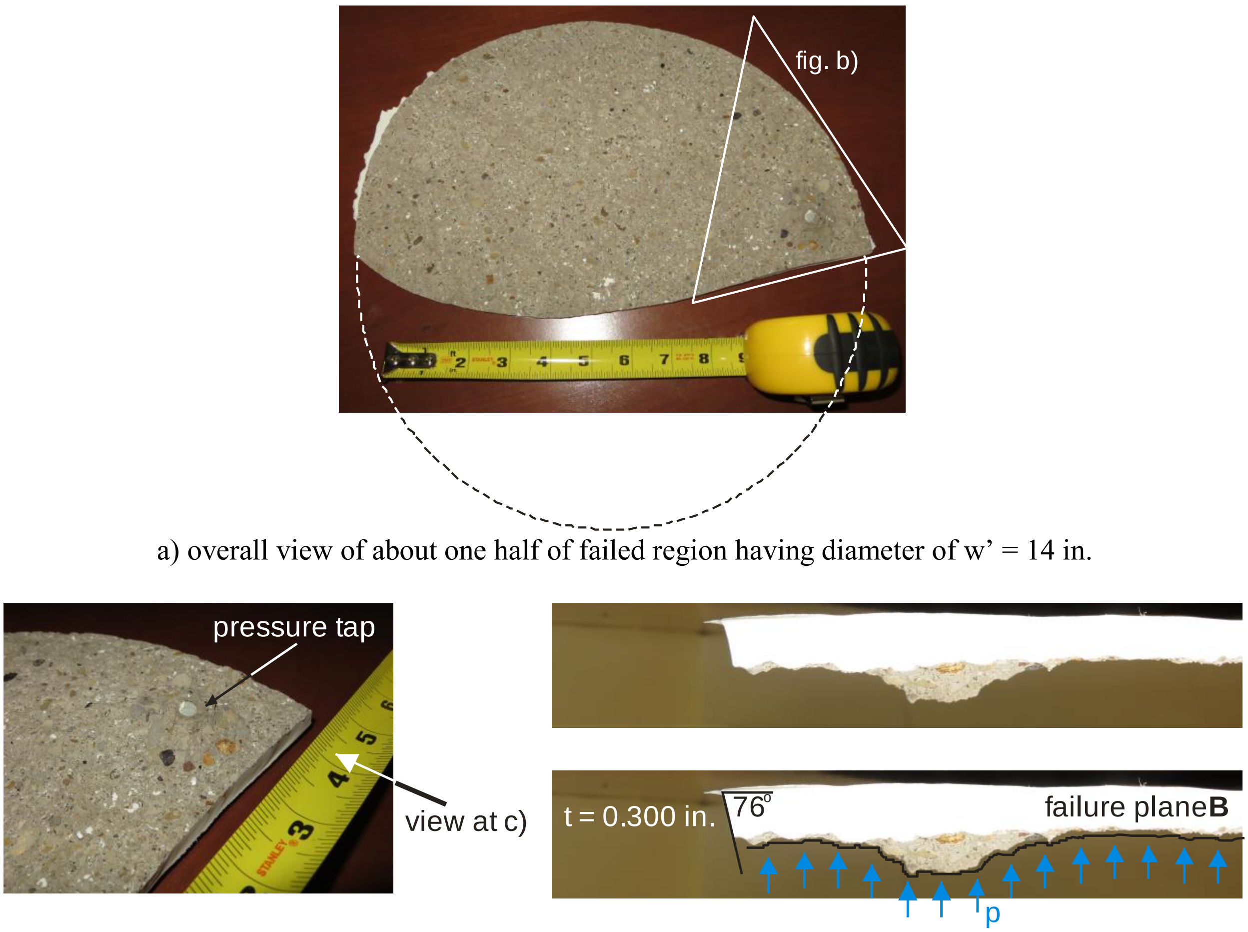
$f_{ev} = pw'/4t$

The average value of f_{ev} was found to be approximately 2700 psi. There is no reported shear strength for the S-301 epoxy. However based on reported tension (f_t = 7000 psi) and compression (f_c = -12000 psi) capacities (Appendix B), one can determine from a Mohr's circle analysis, that a shear capacity f_{ev} = 2700 psi, corresponds to a shear angle

$\theta = 90 - 0.5[\arctan(2f_{ev}/(f_t - f_c)) = 82^o$

This steep angle is consistent with observed type I failures. An example is shown in Figure 12. Thus, the value of f_{ev} = 2700 psi appears consistent with both test results and reported material properties.

Figure 12 also illustrates the uniform failure through the cover concrete (failure plane **B** in Figure 1) resulting from the largely tensile response as pressure builds up behind the epoxy. This failure has a similar appearance to that observed in the pull-off tests (Figure 10).



a) overall view of about one half of failed region having diameter of w' = 14 in.

b) region of failure plane near tap

c) cross section of epoxy at failure

Figure 12 Shear failure plane (Specimen 125-15-e).

Epoxy Flexure

No evidence of flexural distress (failure surface **D** in Figure 1) of the epoxy was seen in any test. The experimentally observed flexural stress at failure is determined as:

$f_{er} = 6pw'^2(3+v)/64t^2$

The average value of f_{er} was found to be approximately 95,000 psi whereas the reported flexural modulus of S-301 epoxy is five times this value: 500,000 psi. Thus it is not surprising that no flexural distress was observed.

Implications to Epoxy Application

It is clear that punching shear failure will always control the behaviour of this type of failure due the very high flexural modulus of the S-301 epoxy. The epoxy shear capacity is approximately 2700 psi, about ten times the design concrete shear strength ($4\sqrt{f_c'} \approx 285$ psi). Since the hydrostatic pressure once a delamination has begun is self-equilibrating, this implies that if the epoxy is greater than one tenth the thickness of the concrete substrate, it is possible that the concrete substrate will fail in shear rather than the epoxy. For various reasons this is unlikely but should be considered. An upper limit on effective epoxy thickness for hydrostatic infiltration application is 10% of the concrete substrate thickness.

Table 6 Hydrostatic tests having Type I failures.

Slab and test ID	measured epoxy thickness	measured flaw diameter at failure	ultimate pressure	epoxy shear stress	epoxy flexural modulus
	t	w'	p	$f_{ev} = pw'/4t$	$f_{er} = 6pw'^2(3+v)/64t^2$
	in.	in.	psi	psi	psi
125-15-b	0.283	8	360	2544	89001
125-15-e	0.283	14	430	5318	325564
125-15-a	0.283	11	460	4470	215008
250-15-b	0.369	10	550	3726	124967
250-15-a	0.369	11	440	3279	120968
375-15-e	0.400	11	540	3713	126341
500-15-G-a	0.500	8	460	1840	36432
500-15-G-b	0.500	16	340	2720	107712
500-15-a	0.500	10	530	2650	65588
500-15-W-g	0.500	10	330	1650	40838
500-15-g	0.500	8	325	1300	25740
500-15-h	0.500	11	410	2255	61392
500-40-G-a	0.500	11	440	2420	65885
500-15-W-a	0.500	11	500	2750	74869
500-15-W-j	0.500	10	380	1900	47025
500-25-G-e	0.500	11	510	2805	76366
625-15-b	0.723	20	410	2835	97063
750-15-a	0.858	11	310	994	15764
			Average	2732	95362
			COV	0.400	0.778

References

Harries, K.A., Young, S., McNeice, D., and Warren, D., 2004. Sprayed Epoxy Composite Materials for Structural Rehabilitation. *Proceedings of the 10th Underground Construction Technology Conference*, Houston, January 2004.

Standards Referenced

ASTM C39-12 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

ASTM C78-10 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third Point Loading)

ASTM C496-11 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens

ASTM C497-05 Standard Test Methods for Concrete Pipe, Manhole Sections, or Tile

ASTM D7522-09 Standard Test Method for Pull-off Strength for FRP Bonded to Concrete Substrate

APPENDIX A – TEST RESULTS

HYDROSTATIC TESTS

		flaw size			hydrostatic pressure		failure		
SLAB ID	test	w_x	w_y	avg w	cracking	ultimate	code	w'	effected by…
		(in)	(in)	(in)	(psi)	(psi)		(in)	
500-15-1	A	2.500	2.125	2.313	270	530	I	10	
500-15-1	B	1.625	1.875	1.750	240	340	II	10	test A
500-15-1	C	2.500	1.250	1.875	not tested				test E
500-15-1	D	1.500	1.125	1.313	320	390	II	10	
500-15-1	E	0.750	0.625	0.688	-	360	II	12	
500-15-1	F	1.875	1.500	1.688	-	410	III	12	test E
500-15-3	A	1.375	1.250	1.313	180	325	I	8	
500-15-3	B	1.875	1.750	1.813	250	410	I	11	
500-15-3	C	1.625	1.500	1.563	outlier data		III	12	test E
500-15-3	D	flaw not formed			not tested				
500-15-3	E	1.625	2.250	1.938	240	360	III	12	test F
500-15-3	F	0.750	1.375	1.063	-	360	III	10	
125-15	A	1.500	1.250	1.375	-	460	I-II	11	
125-15	B	1.625	1.875	1.750	200	360	I	8	
125-15	C	1.500	1.750	1.625	-	380	III	10	pull-off test
125-15	D	1.625	1.375	1.500	-	350	III	10	pull-off test
125-15	E	1.250	1.375	1.313	260	430	I	14	
125-15	F	1.250	2.125	1.688	not tested				test E
250-15	A	1.500	1.875	1.688	240	440	I-II	11	
250-15	B	1.625	1.750	1.688	200	550	I	10	
250-15	C	2.250	2.125	2.188	not tested				
250-15	D	1.875	1.750	1.813	-	310	II	10	
250-15	E	1.375	1.750	1.563	260	340	II	12	
250-15	F	1.125	1.125	1.125	-	320	II	10	test E
375-15	A	1.000	2.625	1.813	-	520	V - II	10	V at 400
375-15	B	0.875	1.000	0.938	-	280	II	11	
375-15	C	2.250	2.000	2.125	-	560	III	10	
375-15	D	0.875	1.125	1.000	-	470	II	10	
375-15	E	2.875	1.375	2.125	240	540	I-II	11	
375-15	F	1.000	1.000	1.000	not tested				test E
625-15	A	1.250	0.875	1.063	240	420	II	10	
625-15	B	0.750	1.000	0.875	250	410	I	20	
625-15	C	0.750	0.500	0.625	-	310	III	6	test B
625-15	D	0.875	1.000	0.938	not tested				test B
625-15	E	0.625	0.750	0.688	-	270	III	6	test B
625-15	F	0.750	1.250	1.000	230	380	II	10	
750-15	A	0.875	0.750	0.813	-	310	I-II	11	
750-15	B	0.875	1.000	0.938	-	350	II	10	
750-15	C	1.250	1.625	1.438	220	440	II	10	
750-15	D	1.375	1.250	1.313	not tested				
750-15	E	1.125	1.250	1.188	-	420	II	11	
750-15	F	0.875	1.125	1.000	-	460	II	10	
500-05	A	0.875	0.875	0.875	-	430	II	11	
500-05	B	0.500	0.375	0.438	290	380	II	10	
500-05	C	0.250	0.250	0.250	240	370	II	10	
500-05	D	0.375	0.375	0.375	-	410	II	10	
500-05	E	0.500	0.500	0.500	300	360	II	10	

		flaw size			hydrostatic pressure		failure		
SLAB ID	**test**	**w_x**	**w_y**	**avg w**	**cracking**	**ultimate**	**code**	**w'**	**effected by…**
		(in)	(in)	(in)	(psi)	(psi)		(in)	
500-05	F	0.750	0.625	0.688	250	360	II	10	
500-25	A	4.250	3.500	3.875	-	300	II	10	
500-25	B	flaw not formed			not tested				
500-25	C	2.500	3.625	3.063	-	250	III	12	
500-25	D	1.875	1.750	1.813	not tested				test C
500-25	E	3.125	4.125	3.625	320	650	II	10	
500-25	F	2.875	2.375	2.625	240	350	II	10	
500-15-W1	A	1.500	1.375	1.438	-	500	I-II	11	
500-15-W1	B	1.750	0.875	1.313	not tested				test A
500-15-W1	C	0.875	0.750	0.813	not tested				
500-15-W1	D	1.000	1.125	1.063	not tested				
500-15-W1	E	1.250	1.000	1.125	-	320	II	11	
500-15-W1	F	0.875	0.625	0.750	260	310	III	12	
500-15-W2	A	1.250	1.750	1.500	170	330	I	10	
500-15-W2	B	1.000	1.250	1.125	240	435	II-III	11	
500-15-W2	C	1.125	1.000	1.063	250	510	II	11	
500-15-W2	D	1.125	1.250	1.188	540	380	I-II	10	
500-15-W2	E	1.750	1.625	1.688	240	380	II	11	
500-15-W2	F	1.875	0.875	1.375	240	420	II	10	
500-15-G	A	1.125	1.250	1.188	210	460	I	8	
500-15-G	B	1.250	1.000	1.125	-	340	I	16	
500-15-G	C	0.750	1.000	0.875	190	340	II	10	
500-15-G	D	1.250	1.375	1.313	-	320	II	10	
500-15-G	E	0.875	0.875	0.875	-	360	II	11	
500-15-G	F	1.000	1.125	1.063	-	480	II	10	
500-25-G	A	3.875	4.000	3.938	-	420	II	11	
500-25-G	B	2.625	4.000	3.313	-	410	II	11	
500-25-G	C	2.000	1.875	1.938	300	380	III	12	test A
500-25-G	D	2.125	2.500	2.313	-	530	III	12	test C-A
500-25-G	E	1.750	2.375	2.063	-	510	I-II	11	
500-25-G	F	3.125	3.125	3.125	-	420	II	11	
500-40-G	A	6.500	5.000	5.750	340	440	I-II	11	
500-40-G	B	4.250	4.000	4.125	250	460	II-III	10	
500-40-G	C	3.875	6.125	5.000	250	630	III	12	test A
500-40-G	D	5.000	4.375	4.688	-	280	II	10	
500-40-G	E	3.875	4.125	4.000	240	370	II	11	
500-40-G	F	4.750	4.500	4.625	-	480	II	10	
500-15-V	A	1.500	2.000	1.750	-	280	I-II	11	
500-15-V	B	1.750	0.875	1.313	-	310	II	10	
500-15-V	C	2.000	2.000	2.000	-	180	III	12	
500-15-V	D	1.125	1.250	1.188	-	280	II	10	test C
500-15-V	E	2.000	1.750	1.875	-	280	II	11	
500-15-V	F	0.875	1.000	0.938	260	310	II	10	
500-25-V	A	2.625	2.375	2.500	-	120	I	10	
500-25-V	B	2.625	4.250	3.438	-	100	III	12	test A
500-25-V	C	3.000	2.750	2.875	not tested				test A-E
500-25-V	D	3.375	4.875	4.125	-	130	III	12	test A-C-E
500-25-V	E	2.500	2.000	2.250	-	150	III	12	
500-25-V	F	2.375	2.875	2.625	-	100	I-II	11	test E
500-40-V	A	3.875	7.000	5.438	-	60	III	10	

		flaw size			hydrostatic pressure		failure		
SLAB ID	test	w_x	w_y	avg w	cracking	ultimate	code	w'	effected by…
		(in)	(in)	(in)	(psi)	(psi)		(in)	
500-40-V	B	2.750	2.750	2.750	-	135	III	10	
500-40-V	C	5.000	4.125	4.563	-	85	I	10	
500-40-V	D	6.125	6.500	6.313	-	70	I	8	
500-40-V	E	4.375	4.125	4.250	-	80	IV	0.5	
500-40-V	F	3.750	5.500	4.625	-	100	III	10	
500-15-C2	A	1.750	3.000	2.375	not tested				
500-15-C2	B	1.875	2.500	2.188	-	390	I-II	11	creep test
500-15-C2	C	1.500	2.125	1.813	-	450	III	10	creep test
500-15-C2	D	1.375	1.625	1.500	not tested				
500-15-C2	E	1.000	1.375	1.188	-	420	I-II	11	creep test
500-15-C2	F	1.000	0.875	0.938	-	360	III	11	

PULL-OFF TESTS

SLAB ID	test	measured epoxy thickness, t	pull-off capacity
		(mil)	(psi)
500-15-C1	a	449	309
500-15-C1	b	383	339
500-15-C1	c	447	184
500-15-C1	d	561	315
500-15-C1	e	624	bad test
500-15-C1	f	493	271
125-15	a	254	207
125-15	b	215	326
125-15	c	380	386
250-15	a	397	410
250-15	b	354	270
250-15	c	356	250
375-15	a	376	121
375-15	b	412	301
375-15	c	412	337
625-15	a	767	111
625-15	b	701	153
625-15	c	702	200
750-15	a	808	152
750-15	b	905	129
750-15	c	863	125
500-15-W1	a	514	250
500-15-W1	b	451	281
500-15-W1	c	542	277
500-15-W1	d	482	254

APPENDIX B – EPOXY AND MASTIC MATERIAL DATA SHEETS

Certified Applicators of Non Toxic No Dig Restoration Systems

Warren Environmental, Inc.

S-301 Epoxy Spray System
Product Code 301-14

DESCRIPTION: A two part, highly thixotropic epoxy system formulated for spraying with Warren Environmental, Inc.'s patented meter/mix spray equipment.

CHARACTERISTICS: Formulated with special additives and modifiers to enhance the water resistance, chemical resistance, and bond strength to a variety of substrates as well as its own internal strength. The high thixotropic index allows for up to a ¼" build-up on vertical surfaces without sag.

APPLICATION: Designed for use with Warren Environmental's patented meter, mix and spray equipment. The epoxy component utilizes a 2 parts base to 1 part activator mix ratio by volume. This product is sold and installed only by technicians specifically trained and licensed in our patented techniques.

ADVANTAGES:

% Long Open time for Efficient Topcoating
% Excellent Cure at Low Temperature
% Excellent Cure at High Humidity
% Zero Induction Time
% 0% VOC's
% 100% Solids
% Long Working Time Relative to Cure Time
% Ready-to-Use (No Thinning Required)
% Excellent Water and Chemical resistance with ambient cure
% Achieve high-build thicknesses without sag

CERTIFICATION:

None

SPECIAL SAFETY AND HANDLING: There are no special safety or handling procedures beyond those published on the reverse and the Material Safety Data Sheets.

Typical Properties

Liquid Properties (Systems)

Viscosity	90,000-120,000 cps
Thixotropic Index	5.0-6.0
Specific Gravity	1.162
Flash Point (Closed Cup)	>235°F
Color	Varies
Geltime (200g@77°F)	27 minutes
Thin Film Set (@ 77°F)	2 hours
Thin Film Set (@ 40°F)	8 hours

Physical Properties
(1/8" Casting)

Tensile Strength (ASTM D638-86)	7000 psi
Flexural Strength (ASTM D790-86)	11,000 psi
Flexural Modulus @ 0.100" (ASTM D790-86)	500.000 psi
Compressive Strength (ASTM D695-85)	12,000 psi
Glass Transition Temperature (ASTM D3418-82)	151°F
Tensile Elongation @ Break	4.8%
Thin Film Set (@77°F)	2 hours
Shore D Hardness	83-85

Chemical Resistance
(28 Day Immersion)

Chemical	**Weight Gain (%)**
Toluene	0.99
Ethanol	4.68
10% Acetic Acid	3.85
70% Sulfuric Acid	0.13
50% Sodium Hydroxide	0.09
Distilled Water	1.11
Methanol	9.55
Xylene	0.69
Butyl Cellosolve	1.18
Methyl Ethyl Ketone	11.19
10% Lactic Acid	3.24
Bleach	0.93
1,1,1 Trichloroethane	0.43
10% Nitric Acid	2.05
30% Nitric Acid	4.17

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www.warrenenviro.com E-mail: info@warrenenviro.com

Certified Applicators of Non Toxic No Dig Restoration Systems

Warren Environmental, Inc.

M-301 Epoxy Trowel-On Mastic System
Product Code 301-18

DESCRIPTION: A two part, highly thixotropic epoxy system formulated specifically for trowel-on applications.

CHARACTERISTICS: Formulated with special additives and modifiers to enhance the water resistance, chemical resistance, and bond strength to a variety of substrates as well as its own internal strength. The high thixotropic index allows for build-ups of up to 1½" on vertical surfaces without sag..

APPLICATION: Designed to be applied to a clean surface free of standing water with a notched (toothed) trowel similar to stucco. Alternately, it may be applied using heated tanks, heated lines and Warren Environmental's patented meter, mix and spray equipment. This epoxy system utilizes a 2 parts base to 1 part activator mix ratio by volume. This product is sold and installed only by technicians specifically trained and licensed in our patented techniques.

ADVANTAGES:

% Fast Cure
% Excellent Cure at Low Temperature
% Excellent Cure at High Humidity
% Zero Induction Time
% 0% VOC's
% 100% Solids
% Ready-to-Use (No Thinning Required)
% Excellent Water and Chemical resistance with ambient cure
% Achieve high-build thicknesses without sag

SPECIAL SAFETY AND HANDLING: There are no special safety or handling procedures beyond those published on the reverse and the Material Safety Data Sheets.

Typical Properties

Liquid Properties (Systems)

Viscosity	150,000-250,00 cps
Thixotropic Index	5.5-7.0
Specific Gravity	1.292
Flash Point (Closed Cup)	>235°F
Color	Varies
Geltime (200g@77°F)	40 minutes
Thin Film Set (@ 77°F)	2 hours
Thin Film Set (@ 40°F)	8 hours

Physical Properties
(1/8" Casting)

Tensile Strength (ASTM D638-86)	7000 psi
Flexural Strength (ASTM D790-86)	11,000 psi
Flexural Modulus @ 0.100" (ASTM D790-86)	500.000 psi
Compressive Strength (ASTM D695-85)	12,000 psi
Glass Transition Temperature (ASTM D3418-82)	151°F
Tensile Elongation @ Break	4.8%
Thin Film Set (@77°F)	2 hours
Shore D Hardness	83-85

Chemical Resistance
(28 Day Immersion)

Chemical	Weight Gain (%)
Toluene	0.99
Ethanol	4.68
10% Acetic Acid	3.85
70% Sulfuric Acid	0.13
50% Sodium Hydroxide	0.09
Distilled Water	1.11
Methanol	9.55
Xylene	0.69
Butyl Cellosolve	1.18
Methyl Ethyl Ketone	11.19
10% Lactic Acid	3.24
Bleach	0.93
1,1,1 Trichloroethane	0.43
10% Nitric Acid	2.05
30% Nitric Acid	4.17

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