STRESS ENGINEERING SERVICES INC.

an employee-owned company

Evaluation of Underwater Coating Repairs for Enbridge Line 5

Method #3 Belzona 1161/9382
2018 Testing – Sample #1 and #2

SES Document No.: 1254493-PL-RP-02 (Rev 0)

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Limitations of This Report

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Executive Summary

Stress Engineering Services, Inc. (SES) was contracted by Enbridge to evaluate epoxy coating repair systems that are being considered for use on a section of Enbridge's Line 5, which runs through the Straits of Mackinac in Northern Michigan. The simulated repairs were applied while the pipe was submerged in 38–40°F water having a mineral composition similar to that of the Straits. The hardness of the repaired areas was tested using a Shore D durometer over 7^{+} days to document the curing characteristics of the epoxy. The configuration of each repair area was examined using standard metallographic techniques. Additionally, adhesion testing per ASTM D4541 was conducted in both the original and repaired areas of the coating to determine their relative adhesion after full curing.

A series of tests was conducted in 2017 on different repair materials and application conditions following these guidelines. The results of this original testing and evaluation program by SES were fully documented in a series of reports[1] previously submitted to Enbridge.

Most recently, Enbridge requested that additional testing be conducted during the first half of 2018. The results of the testing using repair Method #3 (M3), a Belzona 1161/9382 epoxy and release film, are summarized in this report.

Results indicated that the M3 Belzona repair material exhibited full cure within 24 hours after application at 38 °F. The epoxy showed excellent adhesion compared to the original coating interface in several repair locations. However, the surface preparation and level of workmanship appeared to have adversely affected some areas of the repair, resulting in the epoxy disbonding from the pipe surface during sectioning. When the pipe surface was thoroughly cleaned before application of the epoxy, excellent surface adhesion readings were obtained, i.e., the highest measured to date during this program.

In general, the Belzona1161 epoxy achieved full-cure hardness quicker than PRTI's X-100 UW composite repair material that was tested in 2017. Belzona 1161 epoxy was also harder than the PRTI composite repair material after the 7-day test cycle. However, the data presented in this report is for incorporation into Enbridge's larger repair material evaluation efforts and does not, in and of itself, identify the best repair option.

[1] See "Evaluation of Underwater Coating Repairs for Enbridge Line 5 – Final Report," SES Document No. 1254493-PL-RP-01 (Rev 0), dated 8 September 2017 (plus related addenda).

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1. Introduction

Stress Engineering Services, Inc. (SES) was contracted by Enbridge to evaluate epoxy coating repair systems that are being considered for use on a section of Enbridge's Line 5, which runs through the Straits of Mackinac in Northern Michigan. The simulated repairs were applied while the pipe was submerged in 38 – 40°F water having a mineral composition similar to that of the Straits. The hardness of the repaired areas was tested using a Shore D durometer over 7 days to document the curing characteristics of the epoxy. The configuration of each repair area was examined using standard metallographic techniques. Additionally, adhesion testing per ASTM D4541, "Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers," was conducted in both the original and repaired areas of the coating to determine their relative adhesion after full curing.

Several repair systems and conditions were tested in 2017; SES has previously issued reports summarizing the results of those tests[1]. Subsequent to those efforts, Enbridge provided four additional sections of 20-inch diameter pipe of the same vintage and construction as Line #5 for tests scheduled in 2018 (Figure 1). Tests #1 and #2 in 2018 involved a Belzona 1161/9382 epoxy repair and release film system, which was designated as repair Method #3 (M3). This report summarizes the findings from these first two tests.



Figure 1: Photograph showing the four pipe sections received from Enbridge for testing in 2018.

2. Method 3, Belzona 1161/9382 (2018 Test #1)

The section of pipe used for 2018 Test #1 is shown in Figure 2. Two test areas were prepared on the pipe:

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(1) A band approximately 6" wide and continuous around the circumference of the pipe (referred to here as the 360° repair) on the east end of the pipe[2]; and

(2) Four 6"x6" areas located at 0°, 90°, 180°, and 270° (referred to here as the patch repairs) on the west end of the pipe.

The surface preparation for these tests included removal of the original outer coating down to the primer and hand-scoring of the exposed area using a rasp. As with previous tests, the sample was submerged in a large tank of water held at 38°F during the repair process and maintained at that temperature for one week to allow curing of the epoxy. The epoxy (Belzona 1161) was applied to the test areas by Ballard Construction personnel, after which each repair was wrapped in release film (Belzona 9382) to hold the epoxy in place during curing.

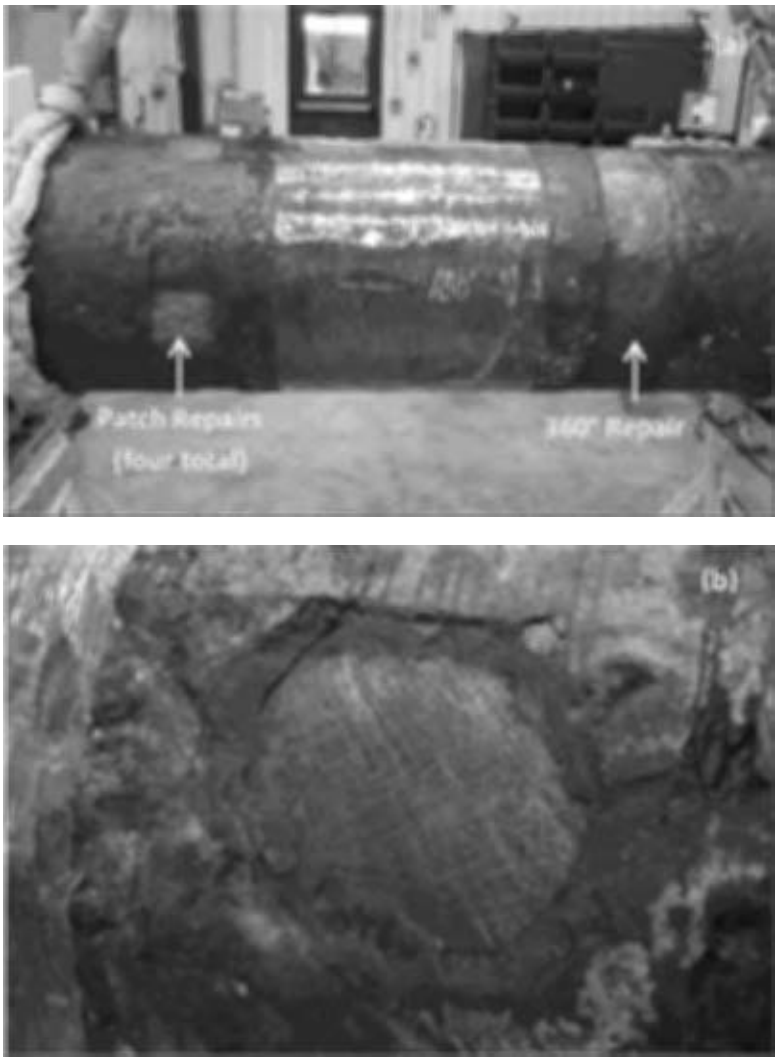


Figure 2: Photographs showing the M3 Belzona 1161 Sample #1 repairs. Photograph (a) shows the repair locations and (b) shows surface preparation condition prior to epoxy application.

[2] Compass directions as oriented in the test tank.

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Hardness tests were conducted every 24 hours after the application of the epoxy at two select locations along the top surface of the pipe. Results shown in Table 1 indicate that the Belzona was fully cured within 24 hours of application[3].

Table 1: Shore D Hardness Results during Belzona Test #1 Cure Cycle*

Sample / Day	Patch Repair at 0°	360° Repair at 0°	Daily Average
1	73	74	**73.5**
2	75	75	**75.0**
3	81	81	**81.0**
4	84	83	**83.5**
5	82	83	**82.5**
6	84	84	**84.0**
7	84	85	**84.5**

***Average of three readings for each sample each day.**

Metallographic sections were removed for examination from three locations on the 2018 Test #1 sample:

- Patch repair at 0°,
- Patch repair at 180°, and
- 360° repair at 90°.

The sections were prepared using the same methods described in previous reports. The 0° patch repair is shown in Figure 3. For this section, the epoxy disbonded from the pipe base metal upon sectioning and the underside of the epoxy exhibited the distinct abrasion pattern used to prepare the pipe surface prior to epoxy application (see Figure 2b).

The other two metallographic sections are shown in Figure 4. The section removed from the 180° patch (Figure 4a) showed good adhesion, as did the epoxy in the 360° repair at 90° (Figure 4b). Neither epoxy coating disbonded from the pipe during sample preparation. SES found that, because the epoxy had been applied by hand by two different people, these specimens showed notable differences in the thickness of the epoxy coating.

Subsequent evaluation of the surface preparation (Figure 2b) revealed that the primer from the original coating had not been removed from the surface of the pipe. The presence of the primer is the likely cause of the varying adhesion observed among the metallographic mounts.

[3] "Full cure" was defined as >Shore D 70 in previous tests.

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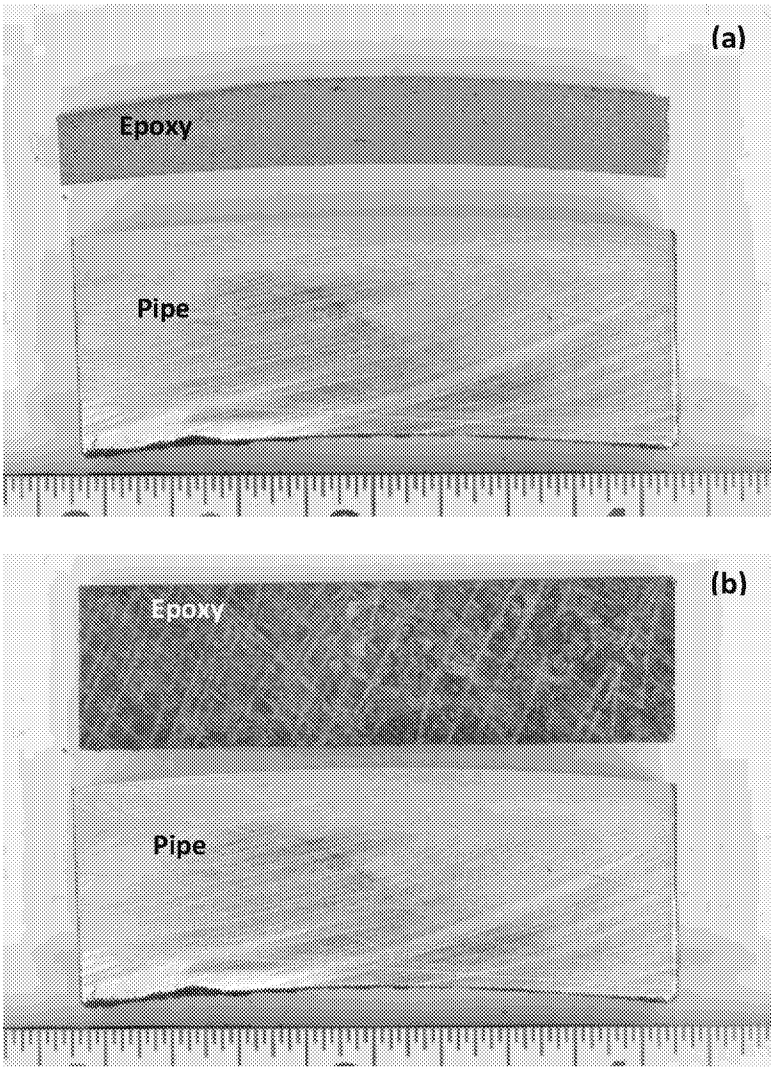


Figure 3: Metallographic section at the 0° patch repair. Photograph (a) shows a transverse (thickness) view of the disbonded epoxy. Photograph (b) shows the underside of the disbonded epoxy.

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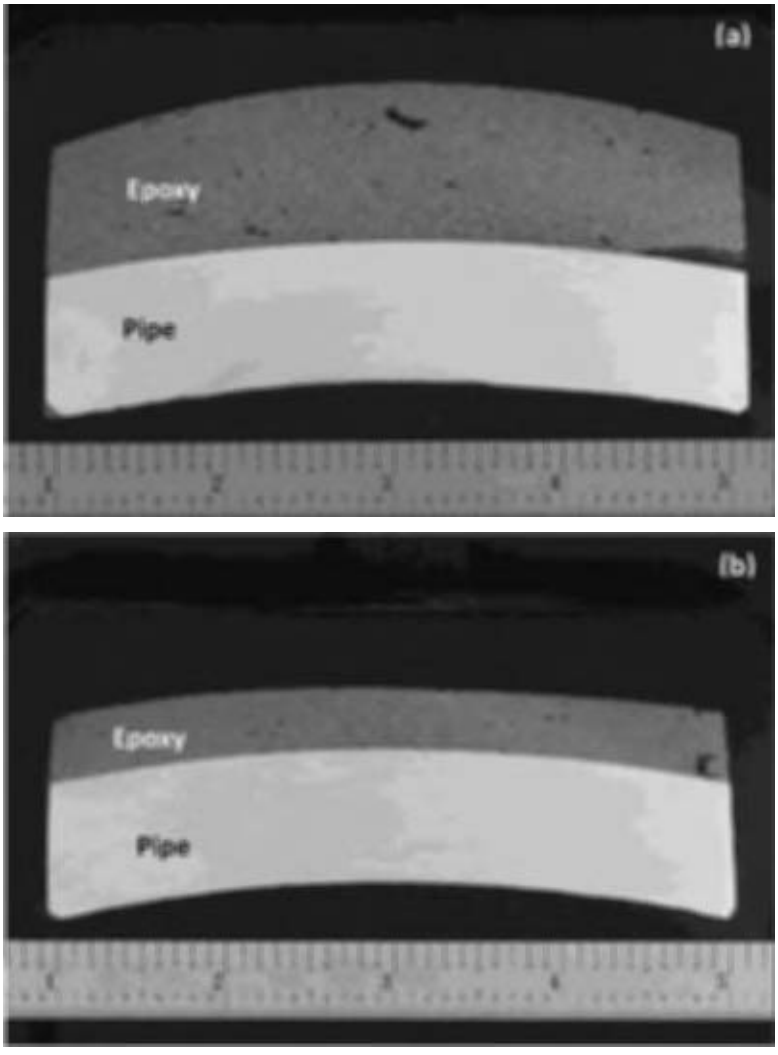


Figure 4: Metallographic sections from the 180° patch (a) and 360° repair at 90° (b).

3. Method 3, Belzona 1161/9382 (2018 Test #2)

SES conducted a second test using the same epoxy repair material as in Test #1. However, for Test #2, the surface preparation was expanded to include further polishing of the repair area and complete removal of the original primer. Additionally, the epoxy coating was applied to each repair by the same person, minimizing the variation in workmanship observed during Test #1.

The pipe section used for Test #2 is shown in Figure 5 prior to surface preparation. Though both patch and circumferential areas were initially prepared, only the 360° circumferential repair was completed in Test #2. A larger area of the original coating was removed to provide a band approximately 18" wide for the circumferential repair. The pipe surface was cleaned using a hand-held side grinder and further polished using wire wheels. After this extensive surface preparation, none of the original coating primer remained on the pipe surface (Figure 6).

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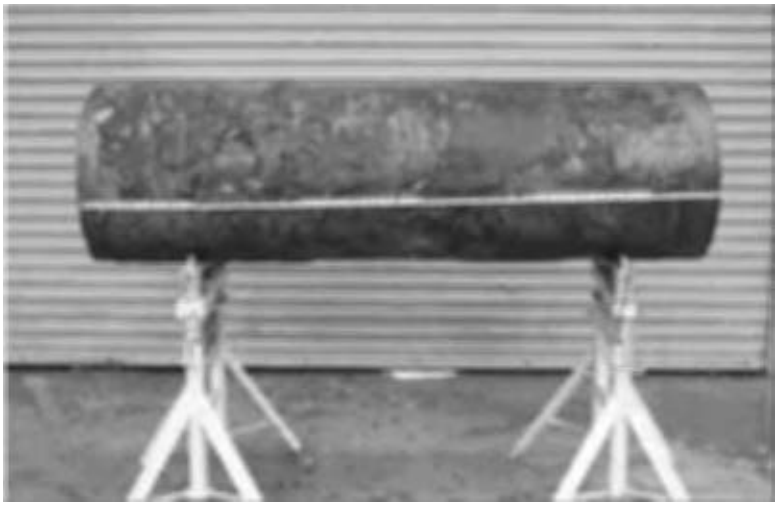


Figure 5: Photograph of the pipe section used for the Belzona Test #2 prior to surface preparation. Numbered divisions on scale are inches.

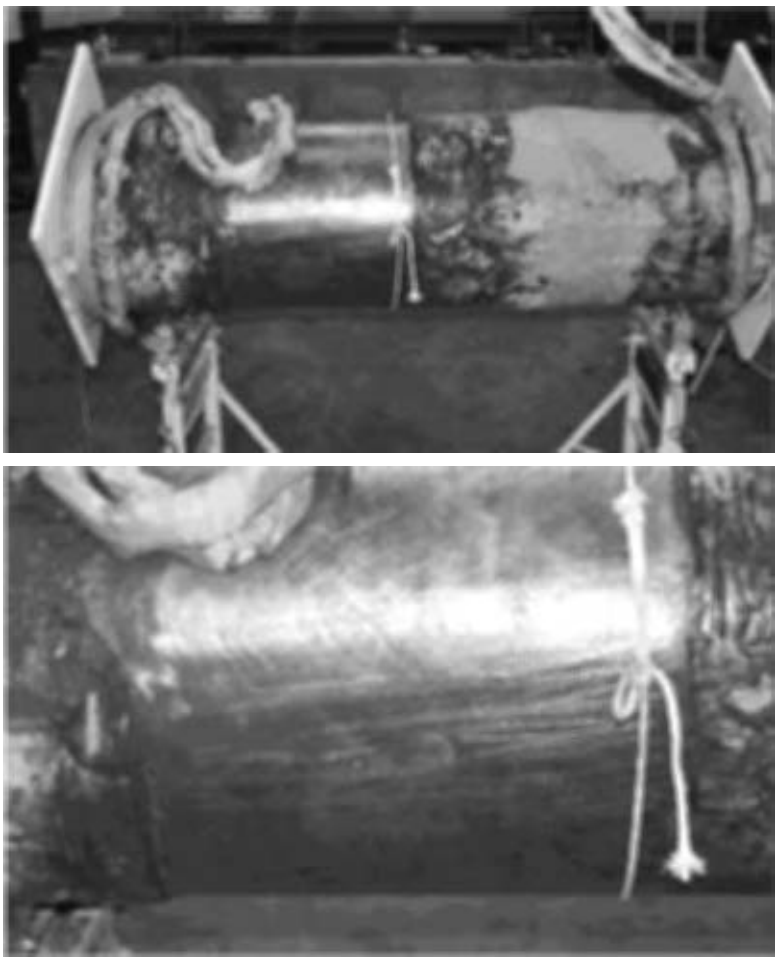


Figure 6: Photographs showing the pipe section used for the Belzona Test #2 after surface preparation.

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As with previous tests, the sample was submerged in a large tank of water held at 38°F during the repair application and for a period of one week to allow curing of the epoxy at field temperature. As planned, the epoxy was applied to the test areas by a single Ballard Construction person, after which the repair was wrapped in release film to support the epoxy in place during curing.

During the curing period, hardness tests were conducted every 24 hours along the top surface of the pipe. Results shown in Table 2 indicate that the Belzona Test #2 repair was fully cured within 24 hours of application and all measurements were very similar to those obtained from Test #1.

Table 2: Shore D Hardness Results during Belzona Test #2 Cure Cycle* Compared to Test #1.

Sample / Day	Test #2 360° Repair	Test #1 360° Repair
1	73	74
2	79	75
3	83	81
4	83	83
5	84	83
6	84	84
7	84	85

***Average of three readings each day.**

Metallographic sections were removed from the 2018 Test #2 360° repair at 0° and 180°. These sections were prepared using the same methods described in previous reports. Both metallographic mounts are shown in Figure 7. Unlike Test #1, the epoxy repairs from Test #2 adhered to both samples during sectioning. Additionally, the thickness of the epoxy was found to be relatively uniform between the top and bottom of the pipe.

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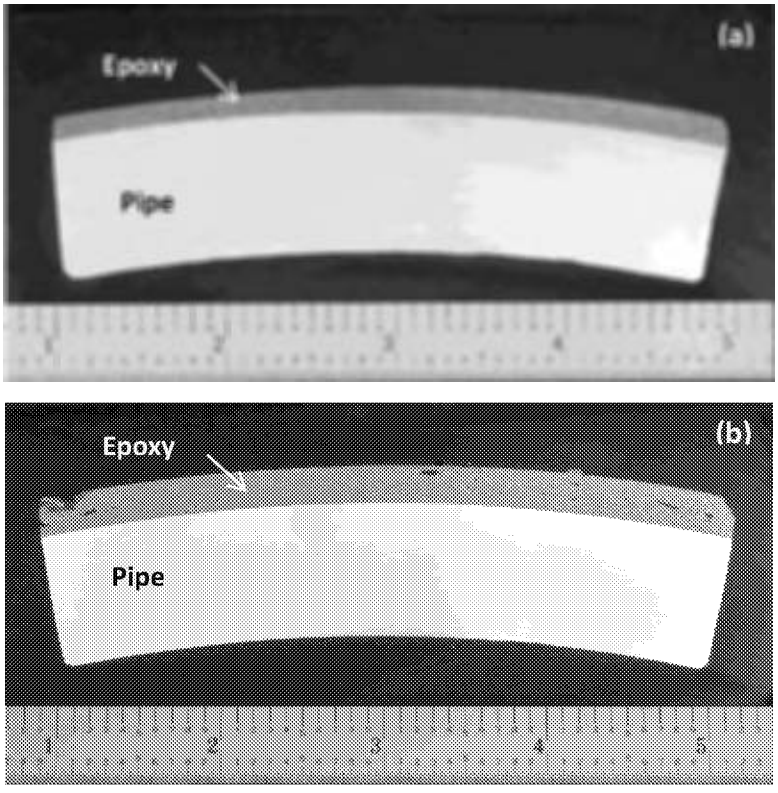


Figure 7: Metallographic sections from the Test #2 360° repair at (a) 0° and (b) 180° locations.

4. ASTM D4541 Adhesion Tests

SES completed ASTM D4541 adhesion tests on specimens from both 2018 Belzona 1161 epoxy repairs. The results (summarized in Table 3) exhibited a large amount of scatter for Test #1. Several of the adhesion test specimens broke during sample preparation. This phenomenon has been noted throughout the testing protocols and is a result of cutting the isolation plug prior to gluing the pull anvil on the coating. In the D1/D2 test (Figure 8), SES obtained relatively good adhesion tests of slightly greater than 600 psi, but the coating on the metallographic mount cut adjacent to the adhesion tests disbonded during sectioning (Figure 3). The scatter and inconsistent results obtained for Test #1 were attributed to the presence of the original coating primer on the pipe surface during the repair, which prevented good adhesion of the repair epoxy.

The additional sample preparation during Test #2 significantly affected the adhesion of the same epoxy repair system. Four plugs were tested at 0° and 180° on the repair; all exhibited high adhesion results, averaging 1,143 and 784 psi, respectively. Additionally, none of the samples broke during isolation cutting of the plug (Figure 9). These are the first tests conducted on repair systems during which no samples broke during sample isolation, including Methods #1 and #2 using a composite wrap. This improved performance is likely a result of the better surface preparation as compared to Test #1.

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Figure 8: Adhesion tests from 2018 Test #1 patch repair, 0° position.

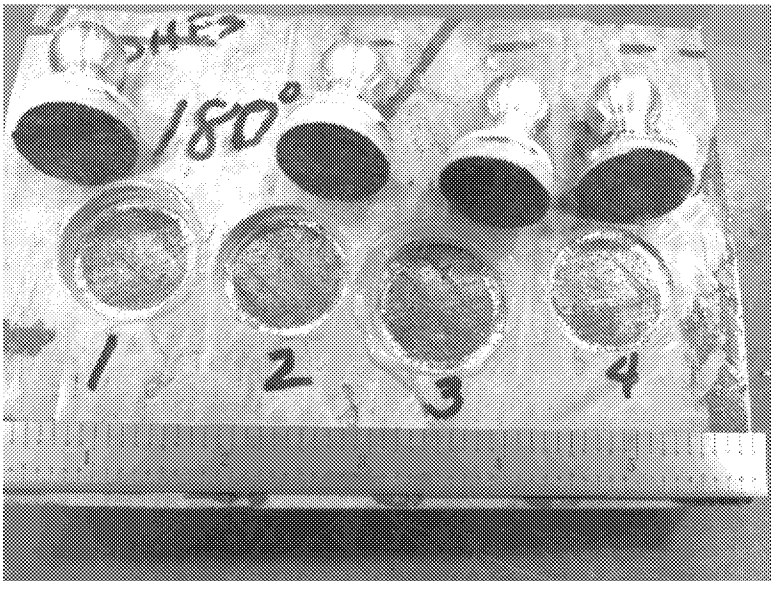


Figure 9: Adhesion tests from Test #2 360° repair, 0° position.

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Table 3: Results of ASTM D4541 Belzona Coating Adhesion Tests.

Sample ID	Repair Type	Position	Readings (psi)	Average (psi)	Comments
Test #1					
A1	360°	90°	n/a	n/a	Coating broke during isolation
A2	360°	90°	n/a		Coating broke during isolation
B1	360°	90°	269	269	
B2	360°	90°	n/a		Coating broke during isolation
C1	Patch	180°	677	791	
C2	Patch	180°	905		
D1	Patch	0°	614	610	Successful adhesion test, but adjacent metallographic sample disbonded
D2	Patch	0°	606		
E1	360°	≈270°	183	99.5	
E2	360°	≈270°	16		
Test #2					
F1	360°	0°	1,403	1,143	
F2	360°	0°	909		
F3	360°	0°	1,313		
F4	360°	0°	948		
G1	360°	180°	589	784	
G2	360°	180°	793		
G3	360°	180°	588		
G4	360°	180°	1,154		

5. Summary and Comparison of Tests to Date

For the work reported here, two 20" diameter pipe samples were repaired with Belzona 1161 epoxy and Belzona 9382 release film (Method 3) in 38°F water. The samples were labeled 2018 Test #1 and Test #2. The only difference between these two tests was the surface preparation, whereby Test #2 removed the majority of the original coating primer. In both cases, the epoxy cured rapidly in 38°F water and exhibited good adhesion as compared to the original coating interface at many repair locations. In Test #1, surface preparation and workmanship during application of the epoxy appeared to have produced varied results. For example, high adhesion numbers were obtained for the patch repair at 0° during the ASTM test, but the epoxy disbonded from the pipe during metallographic preparation, even though the two samples were adjacent to each other on the pipe. Additionally, the thickness of the epoxy varied considerably across a single repair area in Test #1.

In Test #2, complete removal of the original coating primer resulted in improved adhesion results and no disbonding of the epoxy during metallographic or adhesion test preparation. Test #2 represented the

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only repair tested to date during which the repair coating did not break during adhesion plug cutting/isolation.

Table 4 is a summary of all adhesion tests run to date; the average of all tests conducted using each specific repair method is listed. All repairs were cured in 38–40°F water. The data listed for Methods #1 and #2 were obtained during the 2017 tests using PRTI composite wrap, the details of which were provided in a previous report. The data for Method #3 samples (a) and (b) were obtained from 2018 Test #1 with poor surface preparation (where the original primer remained on the pipe surface). Method #3 sample (c) data were obtained from 2018 Test #2 (where the majority of the primer was removed).

As can be noted, the highest adhesion readings to date were obtained for Method #3 sample (c) with the improved surface preparation.

Table 4: Summary of ASTM D4541 Adhesion Tests to Date.

Repair Method	Readings (psi)	Material	Repair Configuration
1	539	PRTI X-100 UW	360° wrap w/ release film
2	304	PRTI X-100 UW	Patch w/ release film
PRTI Baseline	304	PRTI X-100 UW	PRTI Composite wrap (patch), no release film
3a/b	442	Belzona 1161/9382	Belzona Epoxy w/ release film, poor surface preparation
3c	963	Belzona 1161/9382	Belzona Epoxy w/ release film
Belzona Baseline		Belzona 1161/9382	Belzona Epoxy patch, no release film
Original Baseline	208		Original coal tar and primer coating

Table 5 summarizes the average Shore D hardness for each of the repair samples during the cure cycle in 38–40°F water. The hardness cure data for the baseline repair materials (where they were not wrapped in release film but allowed to cure at temperature) are included in the table. These data are also plotted in Figure 10. In general, the Belzona 1161 epoxy achieved a full-cure hardness of 70 Shore D within 24 hours. PRTI's X-100 UW composite repair achieved this same hardness in approximately 5 days. The Shore D hardness of the Belzona epoxy was also harder than the PRTI composite after the 7-day test cycle.

It should be noted that the higher hardness measured in the Belzona epoxy does not of itself indicate that this epoxy is a "better" repair material than the PRTI composite wrap. These data are presented "as is" for incorporation into Enbridge's larger repair material evaluation efforts.

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Table 5: Average Shore D Hardness during Curing of Samples (All Repair Methods).

Repair Method		Method 1	Method 2	Method 3			Baseline	
Repair Material		PRTI Composite	PRTI Composite	(a) Belzona Epoxy	(b) Belzona Epoxy	(c) Belzona Epoxy	Belzona Epoxy	PRTI Composite
Repair Configuration		360° Wrap w/ Stricture	Patch w/ Stricture	360 Wrap w/ Release Film	Patch Repair w/ Release Film	360 Wrap, Polished Surface	Repair Material Only	Repair Material Only
Days after Repair	1			74	73	72	68	
	2	41	43	75	75	79	77	53
	3	58	54	81	81	83	81	60
	4	67	66	83	84	83	81	66
	5	76	73	83	82	84	82	72
	6	75	73	84	84	84	83	76
	7	74	72	85	84	84	83	77

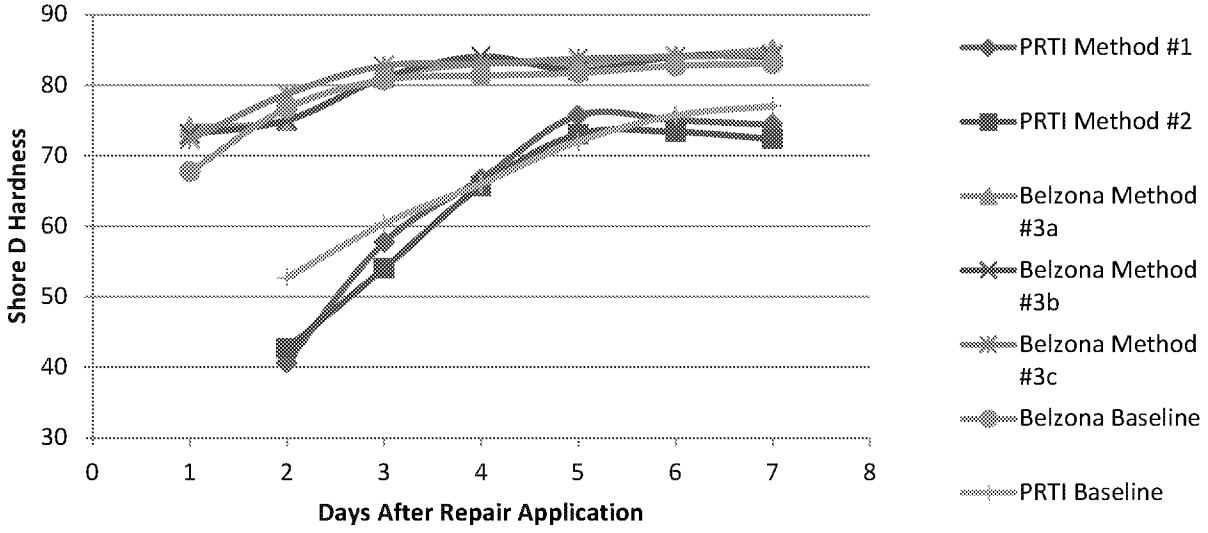


Figure 10: Shore D hardness readings for all repair methods and materials during a 7-day cure cycle. (See Table 4 for descriptions of specific materials and repair configurations.)