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Demonstration and Validation of Controlled Low-Strength Materials for Corrosion Mitigation of Buried Steel Pipes

Final Report on Project F09-AR17

Scott M. Lux, Charles P. Marsh, James B. Bushman,
Bopinder S. Phull, Christopher Olaes, and Larry Clark

December 2015

Bare steel pipe after exposure with cathodic protection in native soil (top); soil cement (bottom left); and flowable fill (bottom right)

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Final report

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Prepared for Office of the Secretary of Defense (OUSD(AT&L))
Washington, DC 20301-3090

Under Project F09-AR17, “Dilute Flowable Backfill Validation for Corrosion Mitigation of Buried Piping at Fort Hood, TX”

Abstract

Researchers investigated the use of controlled low-strength materials (CLSMs) to reduce the corrosion rate of buried steel structures. These thin, self-consolidating cementitious materials, also called “flowable fills,” have an alkaline chemistry that could promote rapid passivation of buried steel surfaces. Two different CLSM blends were tested. Both used cement and a flowability admixture, but one used native soil instead of standard fine aggregate. Using six prepared bare steel pipe specimens, six pipe beds were prepared to evaluate the corrosion-mitigation effects of the two CLSMs used both with and without galvanic cathodic protection (CP). Two control specimens were backfilled using native soil, with and without CP. Commercial probes and instrumentation were used to monitor the specimens for 13 months, logging linear polarization resistance and electrical resistance data for post-exposure evaluation. After excavation, the specimens were also visually inspected for corrosion effects. Results indicated that both flowable fill materials, as used with CP, can effectively mitigate corrosion. Isolated corrosion cells formed where the pipe support pads for the soil cement specimens were improperly installed, resembling isolated corrosion that also appeared on flowable fill specimens without CP. The calculated return on investment for this project was 3.89.

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Preface

This demonstration was performed for the Office of the Secretary of Defense (OSD) under Department of Defense (DoD) Corrosion Control and Prevention Project F09-AR17, "Dilute Flowable Backfill Validation for Corrosion Mitigation of Buried Piping at Fort Hood, Texas." The proponent was the U.S. Army Office of the Assistant Chief of Staff for Installation Management (ACSIM), and the stakeholder was the U.S. Army Installation Management Command (IMCOM). The technical monitors were Daniel J. Dunmire (OUSD(AT&L)), Bernie Rodriguez (IMPW-FM), and Valerie D. Hines (DAIM-ODF).

The work was performed by the Materials Branch (CEERD-CFM), Facilities Division (CF), U.S. Army Engineer and Structures Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL), Champaign, IL. Significant portions of this work were performed by Mandaree Enterprise Corporation, Warner Robins, GA. At the time this report was prepared, Vicki L. Van Blaricum was Chief, CEERD-CFM; Donald K. Hicks was Chief, CEERD-CF; and Kurt Kinnevan, CEERD-CZT, was the Technical Director for Adaptive and Resilient Installations. The Deputy Director of ERDC-CERL was Dr. Kirankumar Topudurti and the Director was Dr. Ilker Adiguzel.

Scott Abraham of the Fort Hood Department of Public Works is gratefully acknowledged for his support and assistance in this project.

The Commander of ERDC was COL Bryan S. Green and the Director was Dr. Jeffery P. Holland.

Executive Summary

In this Corrosion Prevention and Control demonstration, researchers investigated the use of controlled low-strength materials (CLSMs) to reduce the corrosion rate of buried steel structures. CLSMs, also called “flowable fills, are thin, self-consolidating blends of cementitious materials and aggregate that have been used in civil engineering projects since 1964. They can offer engineering and cost benefits in specified applications, but also have an alkaline chemistry that could promote rapid passivation of buried steel surfaces to inhibit corrosion processes. This project was an experimental demonstration that tested the corrosion-control performance of two different CLSMs—one using cement and fine aggregate plus an admixture to promote flowability; the other using the same cement and admixture, but replacing the aggregate with native soil to create a “soil cement.”

Six bare metal pipe sections were abrasive blasted, capped, set on support pads, and buried end to end in a single trench for 13 months at Fort Hood, TX. Two sections each were encased in each experimental CLSM, for a total of four, and two were buried in native soil. Galvanic anode cathodic protection (CP) was applied to one specimen buried in each fill material; the other three specimens had no CP. Corrosion-rate data were collected using linear polarization resistance (LPR) and electrical resistance (ER) probes. After 13 months, the specimens were excavated and assessed.

The demonstrated flowable fills fully prevented corrosion where CP was also applied. Even without CP, both mixtures were largely successful in preventing corrosion. However, some corrosion was present where errors during installation created break in the CLSM encasement.

An important benefit of using CLSMs is that they can significantly reduce the CP current requirement for buried steel. Results showed that the average CP current requirement was reduced by about 44 percent in the CLSM with aggregate; and by about 63% in the soil cement. Therefore, CLSMs can reduce the cost of applying CP to buried steel structures.

The return-on-investment ratio for this project was calculated at 3.89 over 30 years.

Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (US liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
mils	0.0254	millimeters
square feet	0.09290304	square meters

1 Introduction

1.1 Problem statement

Buried steel structures are a significant category of critical infrastructure on military installations, and include sewage systems, industrial waste lines, water-distribution lines, and heat-distribution systems. Maintenance and repair of underground steel structures—particularly corrosion prevention and control requirements—represents a high and continual operational cost for the Department of Defense (DoD). The use of cementitious flowable fill materials, which are also referred to as controlled low-strength materials (CLSMs)[1], offer many potential cost savings as compared with standard cut-and-fill earthwork methods using native soil. In general, CLSMs may be described as reduced-density, self-consolidating cementitious materials that provide more protection from mechanical stresses than native soil while remaining easy to excavate for maintenance. Aggregates may either be standard materials or native soil. According to the National Ready Mixed Concrete Association (NRMCA 2000), flowable fill is

> an economical alternative to compacted granular fill considering the savings in labor costs, equipment and time. Since it does not need manual compaction, trench width or the size of excavation is significantly reduced. Placing flowable fill does not require people to enter an excavation, a significant safety concern. CLSM is also an excellent solution for filling inaccessible areas, such as underground tanks, where compacted fill cannot be placed.

The U.S. government has used flowable fill materials in buried pipeline projects since 1964 (Portland Cement Association 2015). Comprehensive data on the use of flowable fill on military installations are not available, but it may reasonably be assumed that they are specified with some regularity since the technology is mature. However, the use of these materials as a technology for corrosion prevention and control has not previously been demonstrated, validated, and documented.

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[1] In the industry, the two terms are used interchangeably. In the main body of this report, "flowable fill" refers to a CLSM batch using a proprietary admixture; the other demonstrated CLSM is referred to as "soil cement."

A salient characteristic of cementitious CLSMs is that they have an alkaline chemistry, which would be expected to have a passivating effect on the surfaces of buried steel. Therefore, these materials could help both to physically isolate buried steel from corrosive soil chemistry and to reduce the size or voltage requirements of cathodic protection (CP) systems for underground steel structures.

Fort Hood, TX, was selected as the site for an experimental field study to evaluate the corrosion-mitigation performance of two flowable fill materials. Fort Hood was selected on the basis of an established working relationship with the installation on previous CPC demonstrations. The study was performed with the intent of developing engineering specifications for the successful application of CLSMs to mitigate corrosion of buried steel infrastructure at military installations.

1.2 Objective

The objective of this demonstration project was to investigate and validate two engineered flowable fill materials in terms of corrosion-control performance on bare steel pipe specimens, both with and without the application of galvanic cathodic protection.

1.3 Approach

Two CLSMs were designed for this project. One was a cementitious fill using commercial aggregate and a proprietary admixture to improve the flowability of the mixture, which is called “flowable fill” in the body of this report. The other was a thin cementitious blend using native soil as aggregate, which is referred to as “soil cement” to distinguish it from the other CLSM.

Field work and data collection were performed over 13 months (October 2010 – November 2011). The general site-preparation tasks were as follows:

- A single trench was excavated for burial of all test sections end to end.
- Six 10 ft sections of bare steel pipe, each capped at both ends were placed and instrumented for data collection.
- The trench was sectioned with barriers to isolate each pipe section from the others, then the trench sections were filled with different materials—two with flowable fill, two with soil cement, and two with na-

tive soil. Cathodic protection was applied to one pipe specimen buried in each material, while the three remaining sections had no cathodic protection.

The testing program consisted of the following tasks:

- Three soil samples were obtained from the test site at Fort Hood.
- Soil samples were tested in accordance with ASTM D 4318, and also to verify that the soil is "silty sand with the fines (solid particles passing no. 200 sieve) not exceeding 30%."
- Water testing was done to determine the chloride and sulfide content of Killeen, TX, city water and to verify that chloride and sulfide content is less than 0.1% by weight.
- Test batches were formulated in consultation with contractors.
- Three compressive cylinder tests were done for each test batch.
- Slump testing was performed for each test batch.
- Onsite sampling was performed on the day of pours.
- pH tests were performed on all test samples.
- Onsite slump testing of demonstrated flowable fill and soil cement mixes was performed.

The site was monitored by recording data collected from polarization and resistance instrumentation installed at the site. At the end of the demonstration period, the buried pipe sections were excavated and inspected. The test site was restored to its previous condition by backfilling the trenches with the native soil and seeding.

1.4 Scope

The demonstration was performed using capped pipe specimens containing only air. CLSM technology is intended to mitigate corrosion processes affecting the exterior surfaces of buried pipes irrespective of the type of carrier fluid inside. Corrosion of the interior surfaces is not affected by the exterior corrosion regime or the presence of CLSMs, but is controlled by carrier fluid chemistry and other factors.

2 Technical Investigation

2.1 Overview

2.1.1 Materials and equipment

Two types of CLSMs were demonstrated in this project. They are referred to here as "flowable fill" and "soil cement." Table 1 lists the targeted design specifications for the mixes. Both mixes were designed and tested by Rone Engineering, Austin, TX. The demonstration batches were blended by Transit Mix Concrete, Killeen, TX.

Table 1. Targeted design specifications for flowable fill and soil cement mixtures

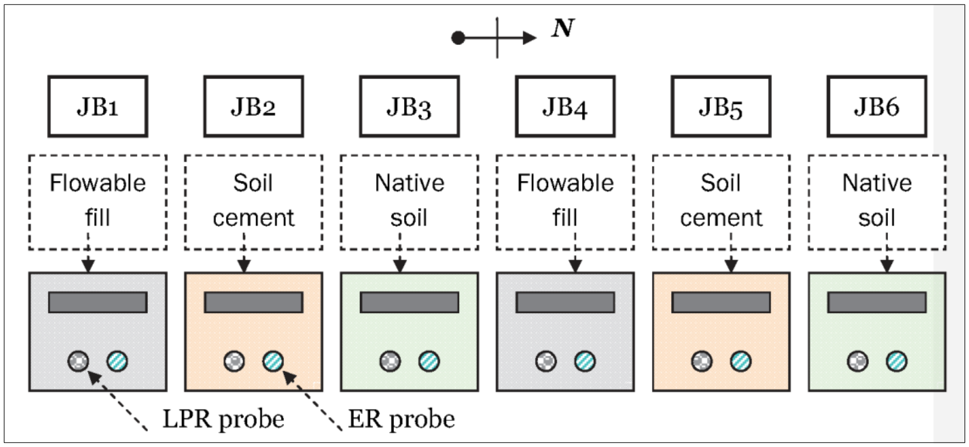
Unit Weight	~ 142 lb/ft^3
Max Slump (in accordance with ASTM C143)	9 in
Water / Cement Ratio	0.68
28-Day Compressive Strength (in accordance with ASTM D4832)	50 – 100 psi

The flowable fill consisted of a mixture of Portland cement (ASTM C-150), fine aggregate, water, and a CLSM admixture marketed under the name DaraFill® (W.R. Grace & Co., Columbia, MD) to enhance flowability. The soil cement consisted of the same cement and admixture, but substituted Fort Hood native soil in place of the fine aggregate. Appendix A reproduces the mix designs for both demonstrated CLSMs, and Appendix B contains the vendor's compression testing reports for both. Appendix C lists other materials and equipment procured to conduct this demonstration.

2.1.2 Steel pipe

Six individual low-carbon steel pipe sections, each 10 ft long and 6 in. diameter, were laid horizontally, end-to-end, in a trench as illustrated in Figure 1. Pipe sections designated JB1 – JB3 were equipped with galvanic cathodic protection (CP) using zinc sacrificial anodes. The other three sections, JB4 – JB6, were not cathodically protected. The pipe sections were separated sufficient to avoid damage to the specimens when they were excavated for inspection and evaluation at the end of the demonstration. The ends of each pipe section were sealed by welding end caps to prevent ingress of fill material to the pipe interior. The pipe sections were grit blasted to white-metal surface before placement in the trench to create a surface with maximum susceptibility to corrosion. For corrosion monitoring, linear polarization resistance (LPR) and electrical resistance (ER) probes were positioned about 6 in. away from each pipe section.

Figure 1. Schematic layout of pipe sections buried end-to-end in trench, showing types of fills used and identification codes for the field tests.



2.1.3 Soil resistivity

The native-soil resistivity was measured using the Wenner 4-pin method, as described in ASTM Standard G57; and by the soil-box method in accordance with ASTM Standard G187. The soil resistivity value was used in cathodic protection design to determine the required current output for the anodes. The soil pH was determined by the antimony electrode method in accordance with ASTM Standard D6569.

Table 2 shows the resistivity readings taken at the Fort Hood demonstration site, which factor into the corrosion-rate calculations performed after the data were collected.

Table 2. Fort Hood soil resistivity measurements.

Pin spacing (ft)	Meter reading (Ω)	Multiplier	Resistance (Ω)	Resistivity (Ω-cm)	Barnes Layer resistivity (Ω-cm)
North					
2.5	5.3	1	5.3	2537	
5	2.6	1	2.6	2490	2442
7.5	1.9	1	1.9	2729	3377
10	1.3	1	1.3	2490	1970
South					
2.5	5.5	1	5.5	2633	
5	3.0	1	3.0	2873	3158
7.5	1.9	1	1.9	2729	2480
10	1.3	1	1.3	2490	1970

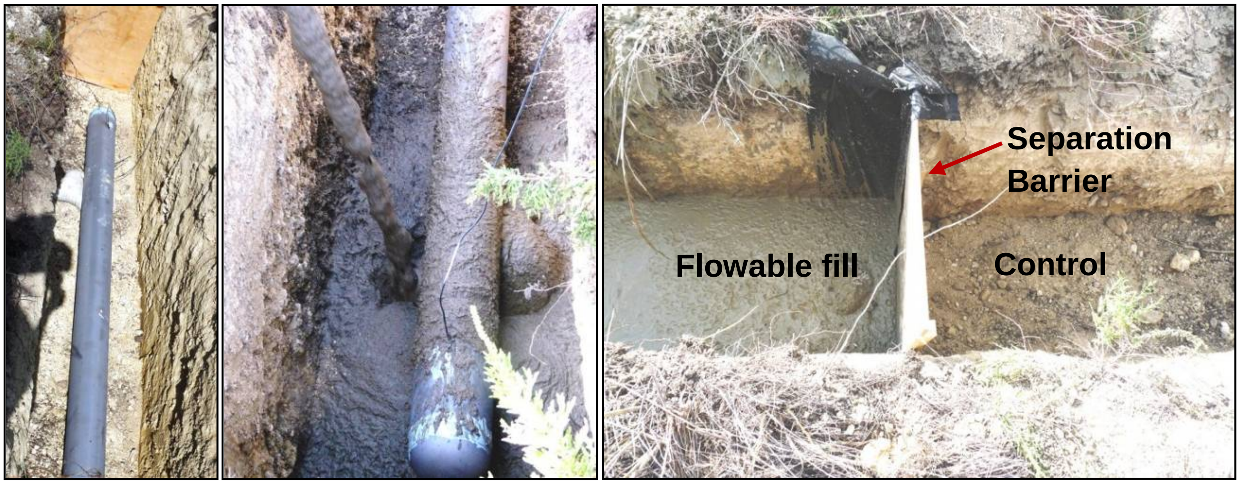
Notes: soil resistivity measured with soil box (2420 Ω-cm); soil pH measured measured using antimony electrode (5.5 Ω); Barnes Layer soil-resistivity calculated from resistivity data.

2.2 Field work

The flowable fill was blended using known, market-available aggregates. The soil cement was prepared using native soil from a location selected by the research team as being suitable for this study. A single trench long enough for the six 10 ft pipe sections was excavated with a backhoe. The trench was deep enough to allow the pipes to be completely encased by 6 in. of fill on top and bottom and more than 9 in. on each side. The pipe segments were laid end-to-end with enough separation between them to avoid damage during post-test excavation. Each segment was supported in the trench by two small pads so the flowable fill could readily flow all the way under and around the pipe and support pads. The specification called for the pads to be woven cotton bags filled with same type of fill as used around each specimen (i.e., flowable fill, soil cement, or native soil). However, at the end of the project, a review indicated that all of the bags had mistakenly been filled with native earth instead of the specified fill. Figure 2 shows a pipe section before, during, and after being buried in flowable fill. A control section representing native-soil without cement is also shown in the figure.

All of the installation steps were documented by video and digital photography. Global Positioning System (GPS) coordinates were recorded to ensure easy identification and location of the pipes.

Figure 2. Illustration of a pipe section before, during, and after encapsulation in flowable fill; native-soil control without cement is on far right.



2.3 Commissioning and monitoring

2.3.1 Cathodic protection and monitoring

A 12 gage TW-insulated seven-strand copper wire was brazed onto the outer surface of each pipe segment at the 12 o'clock position, 6 in. from each end. The brazed connection was masked off with a commercial two-part epoxy coating so that no brazing or copper were exposed. Cathodic protection was provided individually to pipe sections JB1 through JB3 from high-purity ASTM-B-418 Type II prepackaged 30 lb, 2 x 2 x 60 in. galvanic zinc anodes. The number of anodes and center-to-center spacing between the anodes was designed to provide 1.5 – 3 mA/sq ft of current density to bare pipe area. Anodes were installed vertically in native earth 3–5 ft from the pipe at a depth equal to or greater than the pipe, and parallel to the pipe trench. Copper wires from the pipe sections (and anodes, where applicable) were terminated in designated pedestal-mounted plastic test-terminal boxes (test stations) located about 3 ft from the trench. Figure 3 shows an overall view of the test stations adjacent to the buried pipe sections at the test site.

Figure 3. Overall view of the test terminal boxes for the six pipe sections.

For each protected pipe section, a 50 mV/5 A shunt, a shutoff switch, and a rheostat were mounted in the terminal box and connected in series in the circuit. During the course of the project, voltage drop across each shunt was measured periodically with a direct current (DC) voltmeter to calculate current flow. The rheostat was for current flow adjustment, if needed. The shutoff switch was manually used for temporary interruption of the CP current. This allowed measurement of the instant-off potential of the pipe section in relation to a copper/copper-sulfate (Cu/CuSO4) reference electrode to determine the protection level achieved, free of ohmic drop error.

2.3.2 Corrosion rate monitoring

Probes incorporating three identical preweighed cylindrical steel electrodes were prepared and exposed in either the flowable fill or soil cement for determination of instantaneous corrosion rates using the linear polarization resistance (LPR) technique in accordance with ASTM Standard G59. Each probe was installed vertically about six inches away from the pipe surface. One probe was exposed in the native-soil backfill to determine the corrosion rate in the absence of any flowable fill or soil cement. The removable steel electrodes on each probe were mounted in a triangular configuration on short, threaded studs protruding from the probe body

(Figure 4). The insulated test leads from each probe were connected to isolated terminals in the corresponding terminal box.

Figure 4. LPR probes.

At the end of the demonstration project, the LPR electrodes were carefully removed from the probes and examined visually for signs of corrosion.

Commercial electrical resistance (ER) probes (Figure 5) with flush, steel sensing elements were exposed in all of the fills about 6 in. from the pipe surface. The ER technique is based on the principle of calculating corrosion rate from the change in electrical resistance with time due to loss in cross-section thickness of the sensing element by corrosion (ASTM G102). The test leads from each ER probe were terminated in a weatherproof connector, which was housed in the terminal box. Figure 6 shows the typical arrangement of the terminal box with connections, components, and test leads used for each pipe section given cathodic protection from zinc anodes.

Figure 5. Electrical resistance (ER) probe.

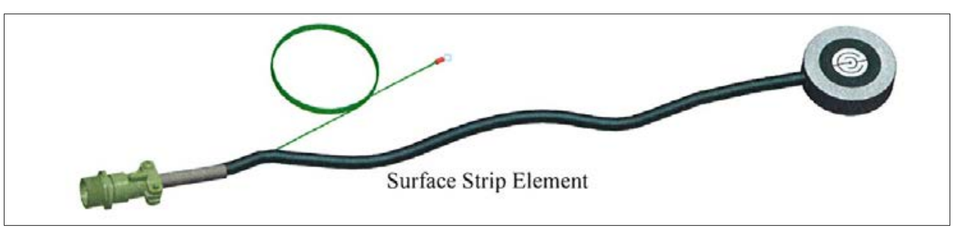
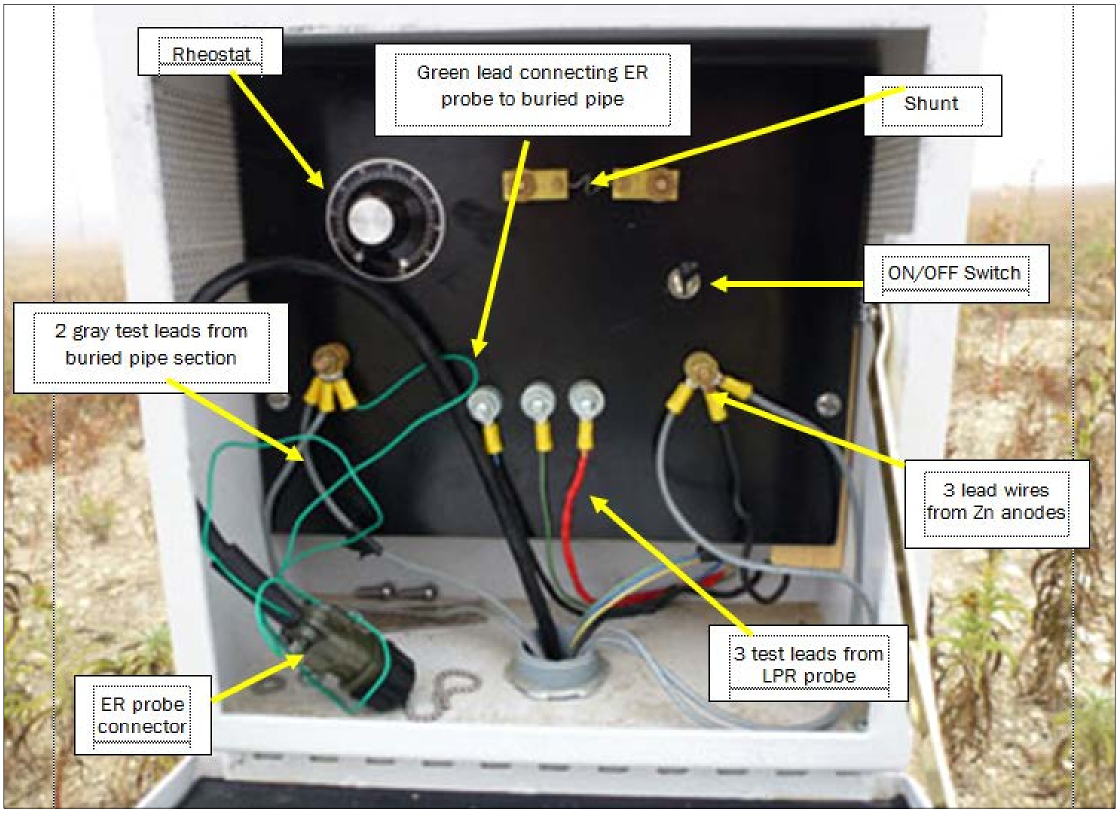


Figure 6. Annotated view of a test terminal box.



The ER probe sensing element was electrically connected to the designated pipe section. Thus, in the case of pipe sections JB1 – JB3, the sensing element also received the same cathodic protection as the corresponding pipe section. The change in electrical resistance of each probe was measured periodically using a Metal Samples MS1500E Handheld ER Corrosion Data Logger (Metal Samples Co., Munford, AL 36268). The ER probes were excavated with the LPR probes and the pipe sections at the end of the project.

2.4 Completion of field work

After 13 months exposure (22 October 2010 – 21 November 2011), the pipe segments and corrosion-monitoring probes were carefully excavated using a backhoe as shown in Figure 7. The LPR and ER probes were extracted at the same time. As much remnant fill as possible was removed from the pipe surfaces and probes so they could be visually inspected to assess the effectiveness of the flowable fill and soil cement in mitigating corrosion (Figure 8). The overall and close-up appearance of the as-removed pipe sections and LPR and ER probes was documented by digital photography both in the field and in the laboratory. A pipe pit-depth gauge was used to measure any pitting that was observed.

Figure 7. Excavation of pipe test sections after 13 months exposure in flowable fill.

Figure 8. Removal of alternative fills and initial pipe inspection after excavation.

3 Discussion

3.1 Metrics

The native-soil resistivity was measured using the Wenner 4-pin method as described in ASTM G57 and by the soil-box method described in ASTM Standard G187.

The soil pH was determined by the antimony electrode method described in ASTM Standard D6569.

Cathodic protection was provided individually to pipe sections JB1 – JB3 from high-purity ASTM-B-418 Type II prepackaged 30 lb. 2 x 2 x 60 in. zinc anodes.

Instantaneous corrosion rates were determined periodically by the LPR technique described in ASTM G102. Using a Gamry Model 600 Potentiostat, a small, single-ramp DC voltage signal was applied between two of the electrodes (starting at -20 mV, ramping through the corrosion potential to completion at +20 mV) at a rate of 7.5 mV/min. The third electrode served as a pseudo-reference electrode. The resultant current between the two electrodes was recorded automatically via the potentiostat software, which was subsequently also used for calculating corrosion rates. The slope of the linear portion of the voltage/current plot represents the linear polarization resistance (R_p). The corrosion current density (i_{corr}) can be computed from the Stern-Geary equation (Stern and Geary 1957):

$$i_{corr} = (\beta_a.\beta_c)/[2.303(\beta_a + \beta_c).R_p]$$

where β_a and β_c represent the anodic and cathodic Tafel slopes of the polarization (potential versus log i) curves, respectively. If the actual β_a and β_c values are unknown, default values of 120 mV/decade can be used in the analysis. When the mode of corrosion is uniform attack, the corrosion current density can be converted to corrosion rate using Faraday's Law in accordance with the following equation:

$$\text{Corrosion rate (mils per year, i.e., mpy)} = 0.1288 \times i_{corr} \times E/\rho$$

where i_{corr} is the current density in μA/cm^2 (i.e., current divided by the metal surface area over which it is being discharged); E is the electrochemical equivalent of the metal (i.e., atomic weight/valency, typically 27.92 for carbon steel); and ρ is the density of metal in g/cm^3 (typically 7.87 for carbon steel); (1 mpy = 0.001 in/yr = 25.4 μm/yr.)

3.2 Results

3.2.1 Flowable fill with galvanic CP (JB1)

Figure 9 shows overall (left) and close-up (right) views of the JB1 pipe section extracted after 13 months of exposure, and Figure 10 shows the LPR and ER probes with no visible corrosion. Since the LPR probes did not have direct cathodic protection, the lack of corrosion is attributed primarily to the high alkalinity of the flowable fill. The LPR data in Table 3 and Figure 11 show that the corrosion rate was mostly very low, except for a few spikes. The low LPR corrosion rate was also confirmed by the ER data summarized in Table 4 and Figure 12. The instant-off potential data shown in Figure 13 show that the pipe section was under complete cathodic protection for most of the project duration (i.e., potential more negative than minus 0.850 V versus Cu/$CuSO_4$ per NACE SP0169 (NACE 2007). The current output varied with the average being 7.5 mA (Table 5).

Figure 9. JB1 pipe section after extraction from flowable fill with CP.

Figure 10. ER probe (left) and LPR probe (right) after extraction from flowable fill specimen JB1.

Table 3. LPR data for JB1 (flowable fill).

Date	Corr Rate (mpy)
10/27/10	0.015
10/28/10	0.003
10/28/10	0.002
11/29/10	0.000
11/29/10	0.001
12/20/10	0.001
12/20/10	0.001
1/26/11	0.342
2/22/11	0.637
3/29/11	0.478
4/2/11	0.001
5/1/11	1.480
5/30/11	0.333
7/3/11	0.271
Average	0.255

Figure 11. LPR corrosion rate versus time data for JB1 (flowable fill).

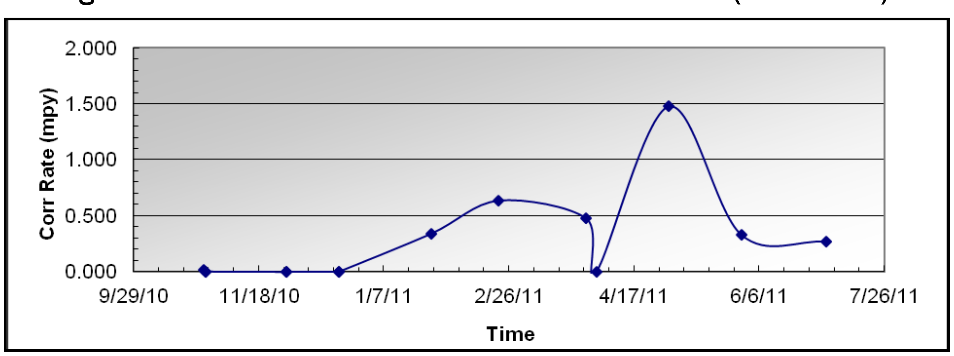


Table 4. ER probe corrosion rate for JB1 (flowable fill).

Date	Corr Rate (mpy)
10/25/2010	0.00
10/26/2010	3.65
10/27/2010	0.00
10/28/2010	18.25
10/29/2010	4.86
11/29/2010	0.42
12/20/2010	0.53
1/26/2011	0.39
2/22/2011	0.09
3/29/2011	0.09
4/19/2011	0.02
5/18/2011	0.07
6/16/2011	0.04
7/19/2011	0.05
8/12/2011	0.05
Average	1.90

Figure 12. ER corrosion rate versus time for JB1 (flowable fill) with cathodic protection.

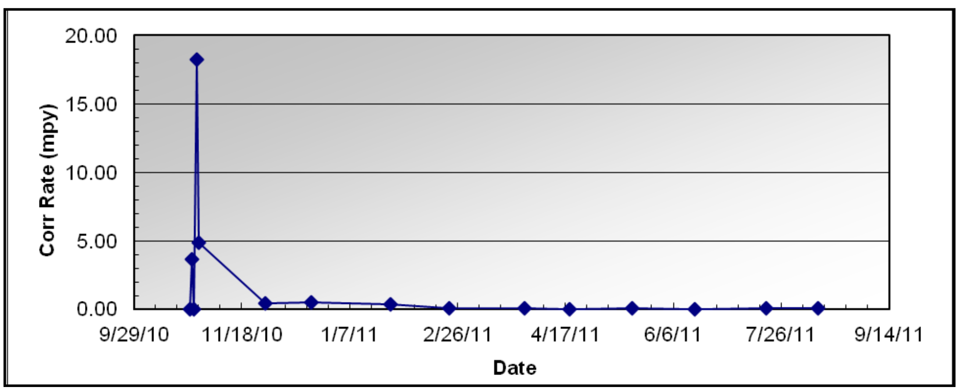
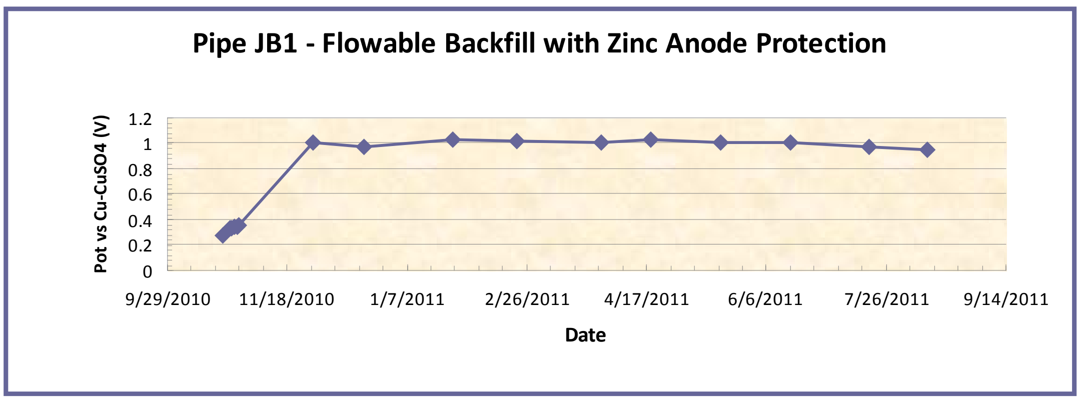


Table 5. Anode current output for JB1.

Date	Anode current output (mA)
10/22/2010	0
10/25/2010	3
10/26/2010	4
10/27/2010	5
10/28/2010	6
10/29/2010	7
11/29/2010	6
12/20/2010	7
1/26/2011	13
2/22/2011	13
3/29/2011	13
4/19/2011	13
5/18/2011	14
6/16/2011	9
7/19/2011	4
8/12/2011	3
Average	7.5

Figure 13. Instant-off potential of cathodically protected pipe section JB1 versus $Cu/CuSO_4$ reference electrode over time (flowable fill).



3.2.2 Soil cement with galvanic CP (JB2)

The overall pipe appeared to be unaffected by corrosion (Figure 14), except for two distinct areas, coinciding with pipe supports in the trench, which showed evidence of corrosion (Figure 15). The LPR and ER probes exhibited no visible corrosion (Figure 16). This was supported by the low LPR corrosion rates (Table 6 and Figure 17). The ER data in Table 7 and Figure 18 indicate no measurable corrosion. The instant-off potential data in Figure 19 indicate that the pipe was under complete cathodic protection most of the time. However, the current output average of 4.9 mA (Table 8) was lower than it was in the flowable fill.

The corrosion observed on the pipe at the support locations is attributed to the lack of passivation provided by the support bags, which had been inadvertently filled with the native desert sandy soil instead of the soil cement. The absence of corrosion on the LPR probes, which were neither cathodically protected nor influenced by the pipe supports, is ascribed to the high alkalinity of the soil cement. Given the lack of corrosion, it is likely that the ER probe benefitted from both the cathodic protection (i.e., no shielding from the current) as well as the high-pH condition.

Figure 14. Overall view (left) and close-up view (right) of pipe section JB2 after extraction from soil cement with CP.

Figure 15. Views of JB2 pipe sections at location of support pads near pipe ends.

Figure 16. ER probe (left) and LPR probe (right) after extraction from the soil cement with JB2.

Table 6. LPR data for JB2 (soil cement).

Date	Corr Rate (mpy)
10/28/10	0.132
10/28/10	0.098
10/28/10	0.082
11/29/10	0.001
11/29/10	0.001
12/20/10	0.001
12/20/10	0.001
1/26/11	0.127
2/22/11	0.077
3/29/11	0.107
4/2/11	0.076
5/1/11	0.000
5/30/11	0.000
7/3/11	0.000
Average	0.050

Figure 17. LPR corrosion rate versus time for JB2 (soil cement).

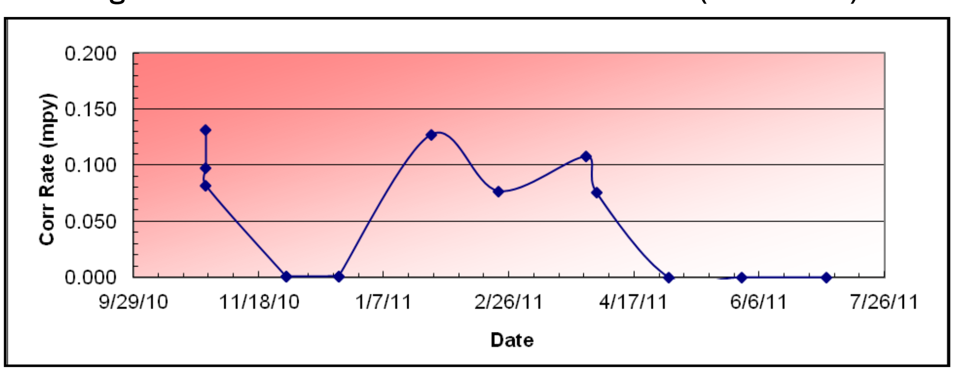


Table 7. ER probe corrosion rate for JB2 (soil cement).

Date	Corr Rate (mpy)
10/25/2010	0.00
10/26/2010	0.00
10/27/2010	0.00
10/28/2010	0.00
10/29/2010	0.00
11/29/2010	0.00
12/20/2010	0.00
1/26/2011	0.00
2/22/2011	0.00
3/29/2011	0.00
4/19/2011	0.00
5/18/2011	0.00
6/16/2011	0.00
7/19/2011	0.00
8/12/2011	0.00
Average	0.00

Figure 18. ER Corrosion rate versus time for JB2 (soil cement) with cathodic protection.

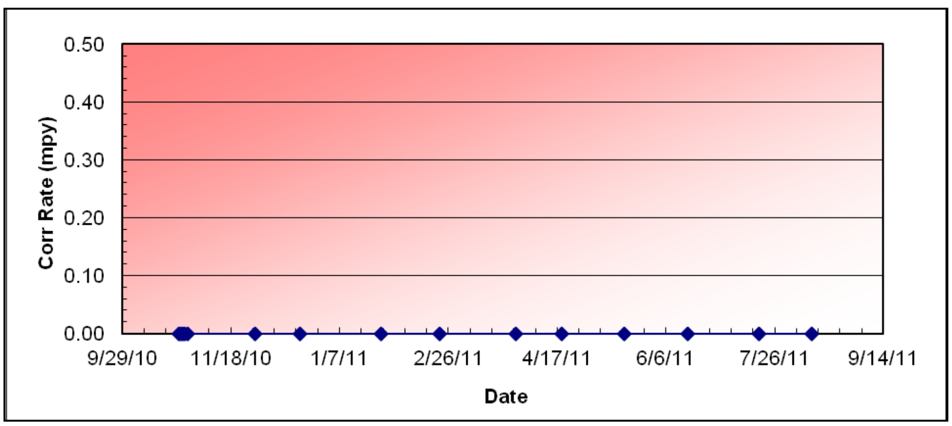
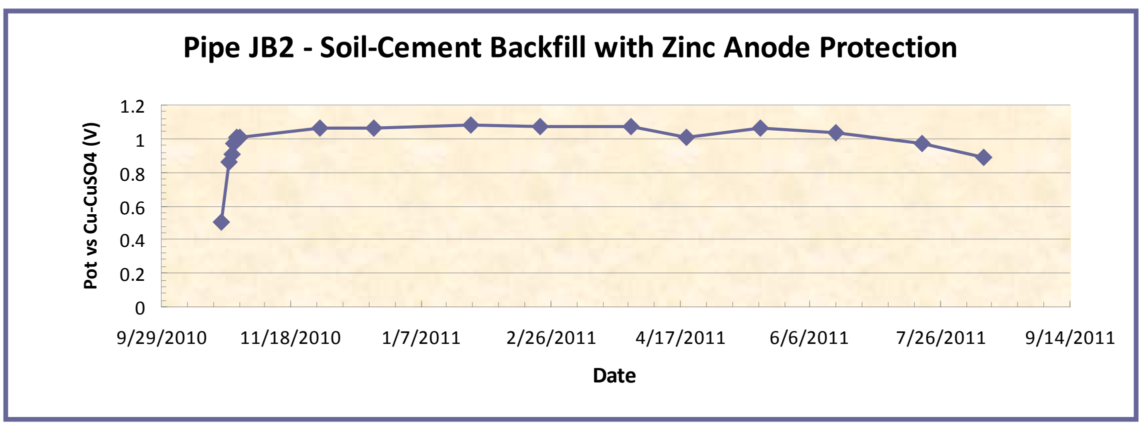


Table 8. Anode current output for JB2.

Date	Anode current output (mA)
10/22/2010	0
10/25/2010	2
10/26/2010	2
10/27/2010	2
10/28/2010	2
10/29/2010	2
11/29/2010	2
12/20/2010	4
1/26/2011	8
2/22/2011	8
3/29/2011	9
4/19/2011	10
5/18/2011	11
6/16/2011	5
7/19/2011	4
8/12/2011	7
Average	4.875

Figure 19. Instant-off potential for JB2 versus Cu/$CuSO_4$ reference electrode over time (soil cement).



3.2.3 Native-soil backfill with galvanic CP (JB3)

This pipe section in native-soil backfill was affected by modest general and localized corrosion (Figure 20) even though it was cathodically protected. Corrosion affected the bottom of the pipe, but little or none on the top half. This is also reflected in the appearance of the LPR probe, which became significantly corroded; while the ER probe, which was under cathodic protection, showed no evidence of such attack (Figure 21). Although the LPR corrosion rates were appreciably greater in this environment (Table 9 and Figure 22) compared to the flowable and soil cement fills, the maximum corrosion rate was still less than 2 mpy, and the average rate was less than 0.5 mpy. The ER data (Table 10 and Figure 23) indicated no measurable corrosion. The instant-off potential data in Figure 24 show that cathodic protection minimum protection level (-0.850 V versus $Cu/CuSO_4$) was not attained until at least a month after the test began. With a native-soil resistivity on the order of 2,500 ohm-cm, pH 5.5 (Table 9), and no cathodic protection during this period, the pipe could have suffered from general corrosion over this interval to create the appearance shown in Figure 20. The maximum depths of the two most significant pits found on the pipe were measured as 11 and 16 mils.

Table 11 shows that, initially, the anode current output was in single digits and reached higher values (16 – 38 mA) for about 6 months in the middle of the test period; before dropping back again to single units. The maximum (38 mA) and average (13 mA) anode current output values were appreciably greater compared to those in the flowable and soil cement fills.

Figure 20. Overall view (left) and close-up view (right) of pipe section JB3 after extraction from native soil with CP.

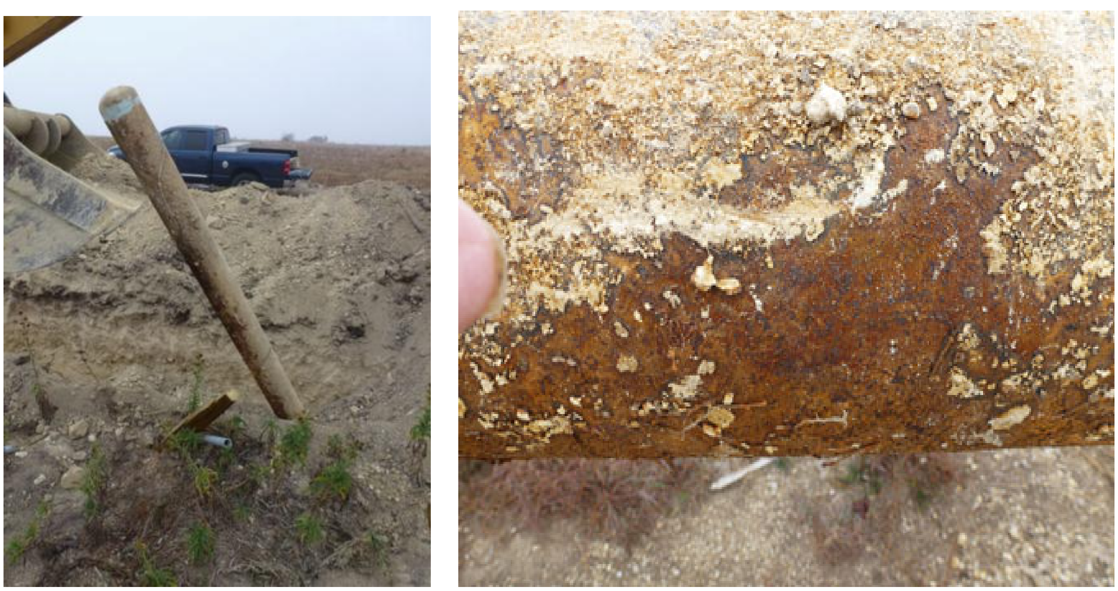


Figure 21. LPR probe (left) and ER probe (right) after extraction from native soil with JB3.

Table 9. LPR data for (JB3).

Date	Corr Rate (mpy)
10/28/10	0.051
10/28/10	0.051
10/28/10	0.051
11/29/10	0.043
11/29/10	0.045
12/20/10	0.041
12/20/10	0.041
1/26/11	0.304
2/22/11	0.456
3/29/11	1.692
4/2/11	1.346
5/1/11	1.136
5/30/11	0.317
7/3/11	0.338
Average	0.422

Figure 22. LPR corrosion rate versus time for JB3 (native-soil).

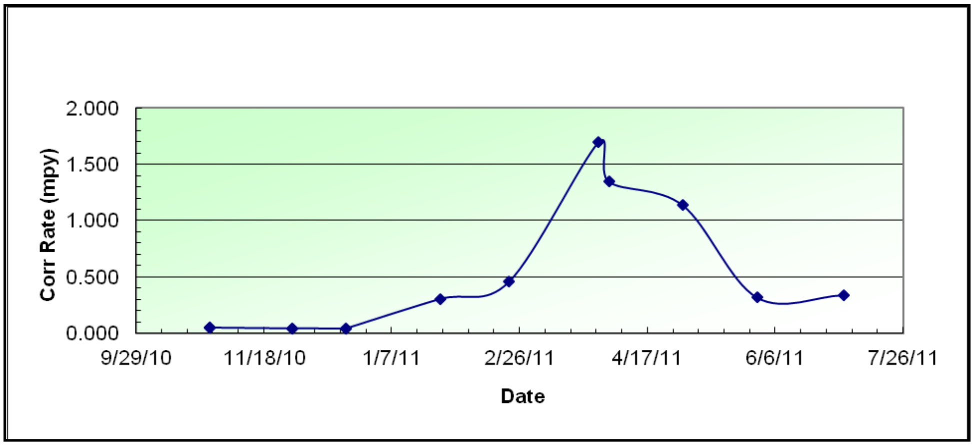


Table 10. ER probe corrosion rate (JB3).

Date	Corr Rate (mpy)
10/25/2010	0.00
10/26/2010	0.00
10/27/2010	0.00
10/28/2010	0.00
10/29/2010	0.00
11/29/2010	0.00
12/20/2010	0.00
1/26/2011	0.00
2/22/2011	0.00
3/29/2011	0.00
4/19/2011	0.00
5/18/2011	0.00
6/16/2011	0.00
7/19/2011	0.00
8/12/2011	0.00
Average	0.00

Figure 23. ER corrosion rate versus time for JB3, native-soil backfill with cathodic protection.

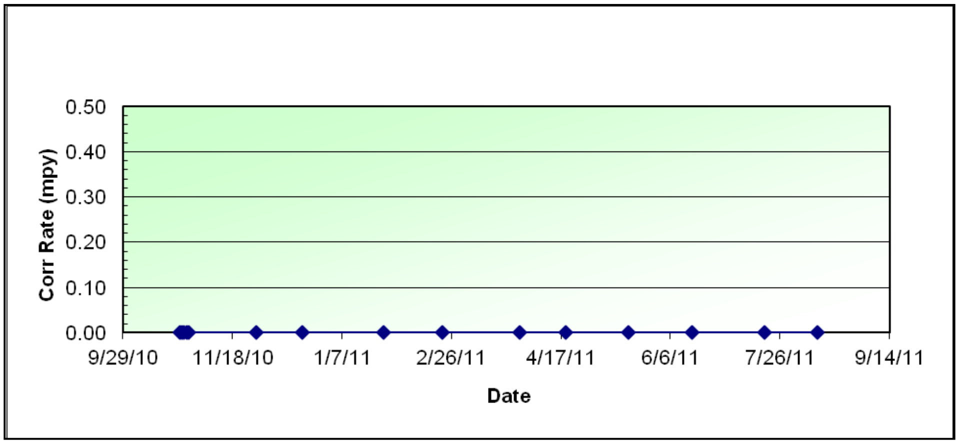
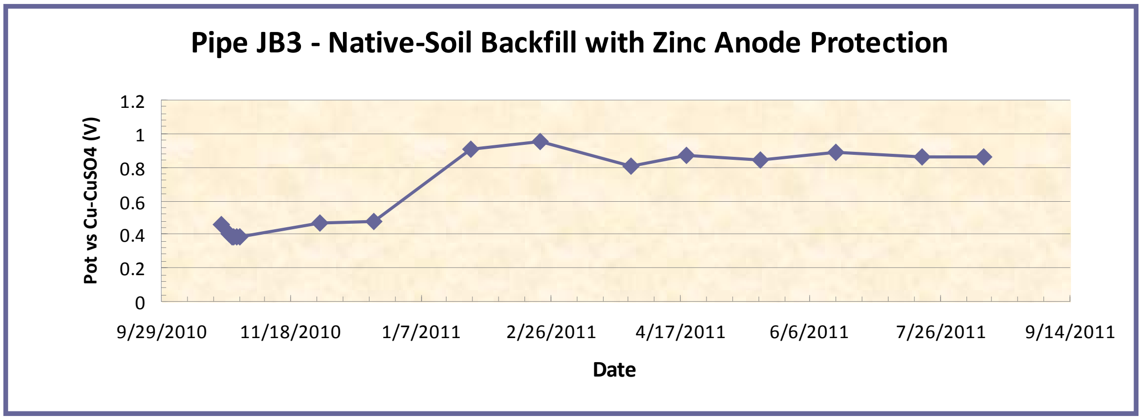


Table 11. Anode current output for JB3.

Date	Anode current output (mA)
10/22/2010	0.0000
10/25/2010	2
10/26/2010	4
10/27/2010	4
10/28/2010	7
10/29/2010	8
11/29/2010	7
12/20/2010	16
1/26/2011	25
2/22/2011	22
3/29/2011	32
4/19/2011	26
5/18/2011	38
6/16/2011	11
7/19/2011	6
8/12/2011	5
Average	13.313

Figure 24. Instant-off potential of cathodically protected JB3 versus $Cu/CuSO_4$ reference electrode over time in native-soil backfill.



3.2.4 Flowable fill without cathodic protection (JB4)

Figure 25 shows that the pipe section in flowable fill without cathodic protection was unaffected by corrosion except at the locations corresponding to the pipe-support pads. No corrosion attack was seen on the LPR or ER probes (Figure 26). The LPR data are summarized in Table 12 and Figure 27. The ER data are summarized in Table 13 and Figure 28. Typical free corrosion potentials shown Figure 29 are on the order of about −0.250 V versus the $Cu/CuSO_4$ reference electrode. These are indicative of steel passivated by the alkaline flowable fill, which is reminiscent of reinforcement bar passivation in highly alkaline concrete. Corrosion occurring at areas corresponding to the pipe support locations cannot be attributed to CP current shielding since the JB4 specimen was not set up with cathodic protection. This corrosion appears to have been caused by the lack of passivation resulting from the inadvertent filling of the support-pad bags with native-soil instead of the flowable fill.

Figure 25. Overall view (left) and close-up view (right) of JB4 after extraction from flowable fill without CP.

Figure 26. ER probe (left) and LPR probe (right) after extraction from flowable fill with JB4.

Table 12. LPR data for JB4.

Date	Corr Rate (mpy)
11/30/10	0.001
11/30/10	0.001
12/20/10	0.031
12/20/10	0.028
1/26/11	0.409
2/22/11	0.247
3/29/11	0.067
4/2/11	0.217
5/1/11	0.014
5/30/11	0.011
7/3/11	0.022
Average	0.095

Figure 27. LPR corrosion rate over time for JB4 in flowable fill.

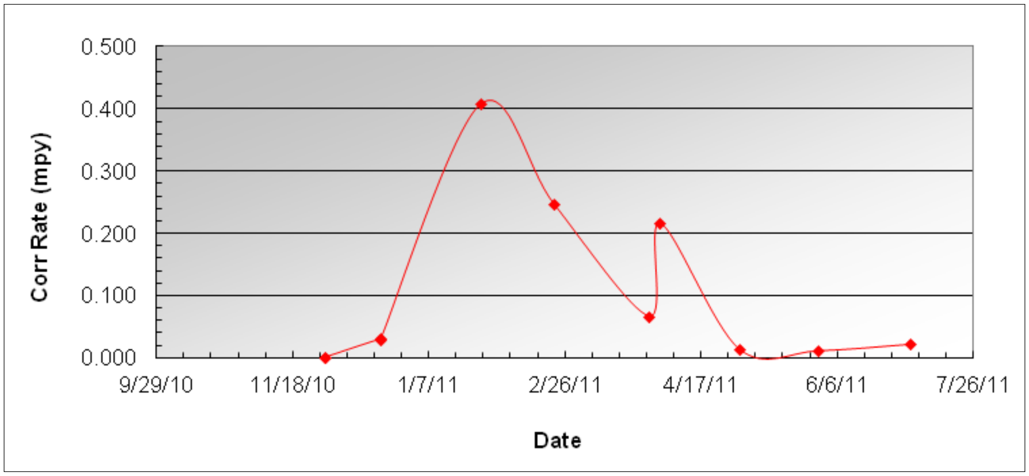


Table 13. ER probe corrosion rate for JB4.

Date	Corr Rate (mpy)
10/25/2010	0.00
10/26/2010	0.00
10/27/2010	0.00
10/28/2010	0.00
10/29/2010	2.43
11/29/2010	0.00
12/20/2010	0.06
1/26/2011	0.00
2/22/2011	0.03
3/29/2011	0.00
4/19/2011	0.00
5/18/2011	0.00
6/16/2011	0.00
7/19/2011	0.00
8/12/2011	0.00
Average	0.17

Figure 28. ER corrosion rate versus time for JB4 in flowable fill, no cathodic protection.

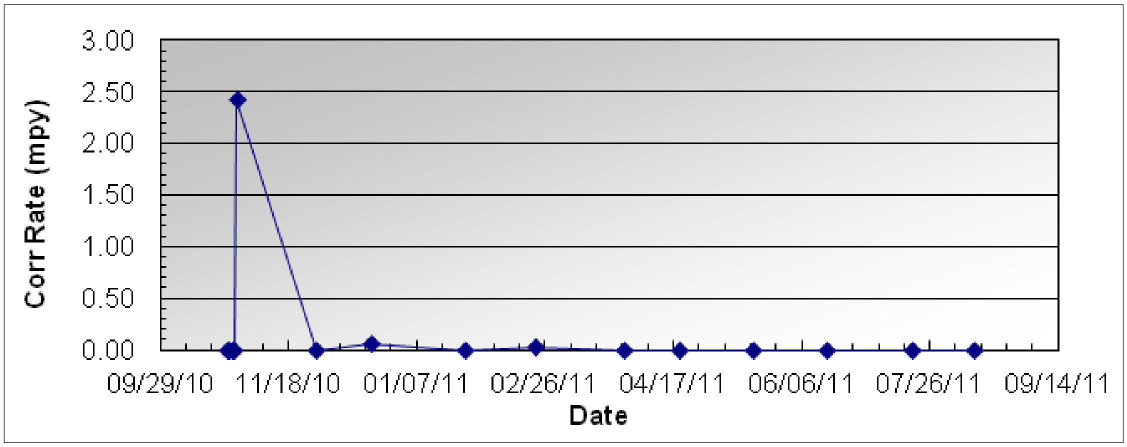
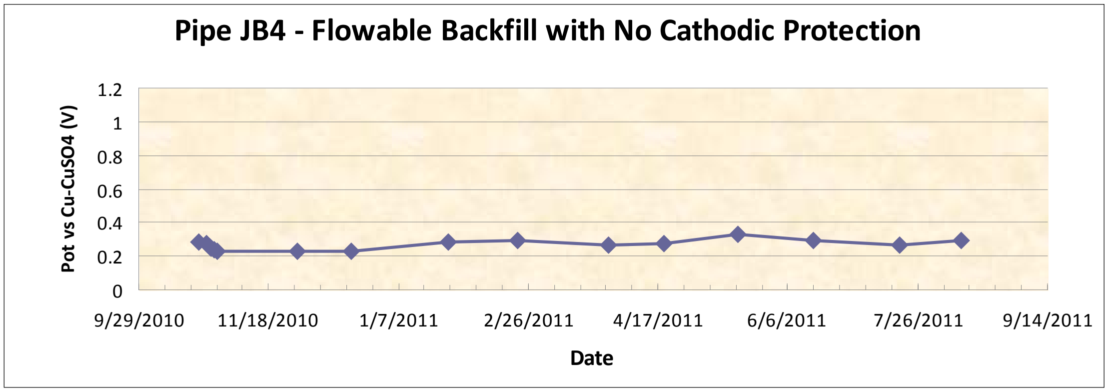


Figure 29. Free corrosion potential of pipe section JB4 versus Cu/$CuSO_4$ reference electrode over time in flowable fill.



3.2.5 Soil cement without cathodic protection (JB5)

The corrosion activity in the soil cement for specimen JB5 was similar to that found in the flowable fill used with JB4. The appearance of the pipe is shown in Figure 30. There was corrosion only at where the pipe-support pads were located. The LPR and ER probes exhibited no visible corrosion (Figure 31). The LPR data in Table 14 and Figure 32 and the ER data in Table 15 and Figure 33 attest to the condition of the probes upon excavation. The free corrosion potentials (Figure 34) were somewhat more active than those in the case of JB4.

Figure 30. Overall view (left) of JB5 pipe section JB5
after extraction from soil cement without CP..

Figure 31. ER probe (left) and LPR probe (right)
after extraction from soil cement with JB5.

Table 14. LPR data for specimen JB5.

Date	Corr Rate (mpy)
10/28/10	0.004
10/28/10	0.004
10/28/10	0.005
11/30/10	0.001
11/30/10	0.001
12/20/10	0.037
12/20/10	0.033
1/26/11	0.009
2/22/11	0.101
3/29/11	0.078
4/2/11	0.026
5/1/11	0.032
5/30/11	0.001
7/3/11	0.001
Average	0.024

Figure 32. LPR corrosion rate versus time for JB5 in soil cement.

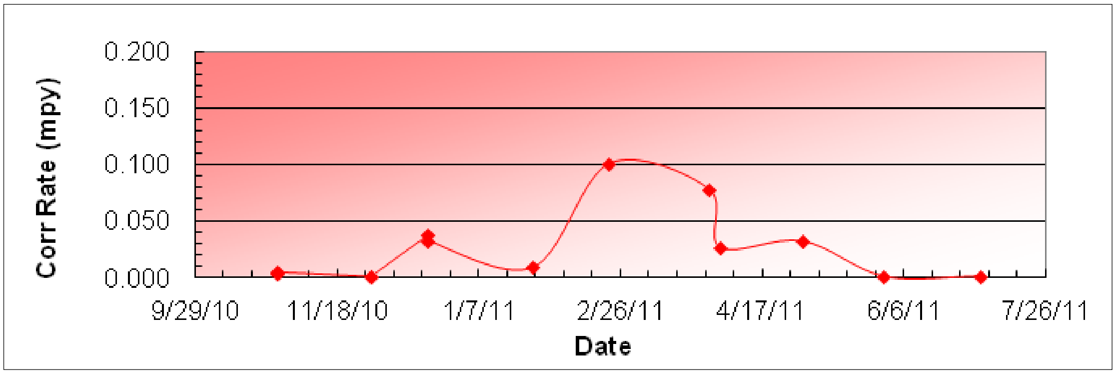


Table 15. ER probe corrosion rate (JB5).

Date	Corr Rate (mpy)
10/25/2010	0.00
10/26/2010	0.00
10/27/2010	0.00
10/28/2010	1.82
10/29/2010	1.21
11/29/2010	0.00
12/20/2010	0.00
1/26/2011	0.11
2/22/2011	0.00
3/29/2011	0.00
4/19/2011	0.00
5/18/2011	0.00
6/16/2011	0.00
7/19/2011	0.00
8/12/2011	0.00
Average	0.21

Figure 33. ER corrosion rate versus time for JB5 in soil cement with no cathodic protection.

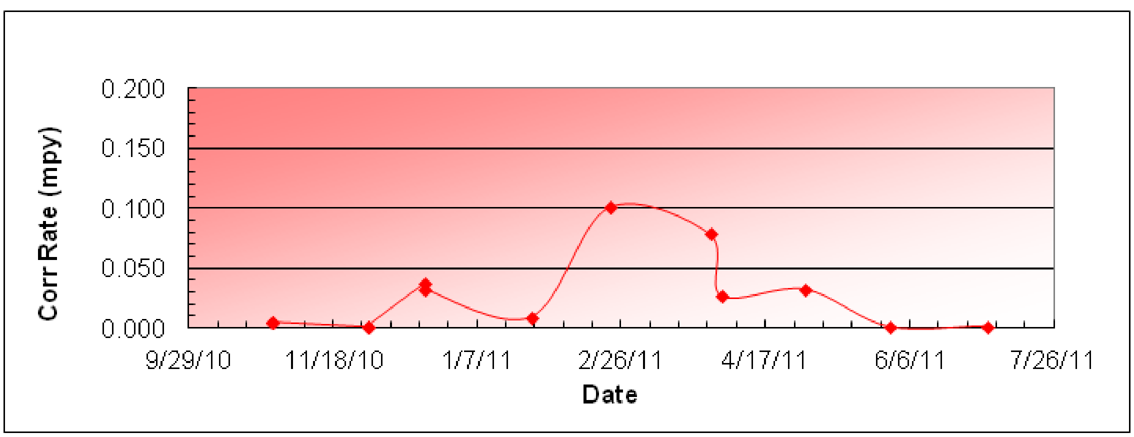
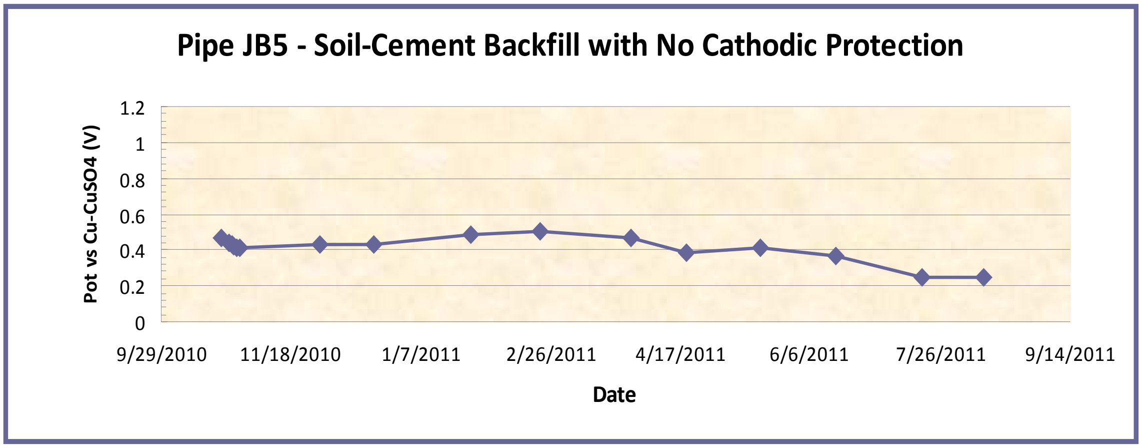


Figure 34. Free corrosion potential of pipe section JB5 versus $Cu/CuSO_4$ reference electrode with time in the soil cement.



3.2.6 Native-soil backfill without cathodic protection (JB6)

The pipe section exhibited very aggressive general and localized corrosion, as illustrated in Figure 35. The LPR and ER probes also exhibited appreciable corrosion (Figure 36). The average LPR corrosion rate (Table 16 and Figure 37) was an order of magnitude higher than those recorded for JB4 and JB5. The ER data (Table 17 and Figure 38) also broadly reflected this trend. Actual pit depths of 20, 31, and 49 mils were measured on the pipe. The free corrosion potential (Figure 39) was generally higher than for specimens JB4 and JB5.

Figure 35. Overall view (left) and close-up view (right) of specimen JB6 after extraction from native soil without CP.

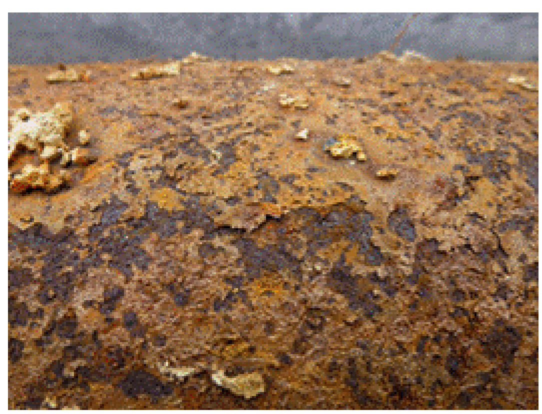


Figure 36. ER probe (left) and LPR probe (right) after extraction from native-soil backfill with JB6.

Table 16. LPR data for JB6.

Date	Corr Rate (mpy)
10/28/10	0.330
10/28/10	0.333
10/28/10	0.342
11/30/10	0.073
11/30/10	0.075
12/20/10	0.087
12/20/10	0.089
1/26/11	1.886
2/22/11	1.527
3/29/11	2.299
4/2/11	1.825
5/1/11	2.359
5/30/11	0.715
7/3/11	0.457
Average	0.886

Figure 37. LPR corrosion rate versus time for JB6 in native-soil backfill.

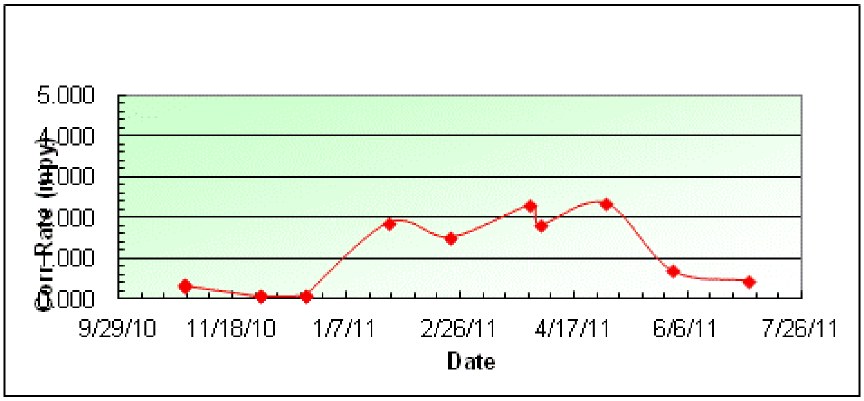


Table 17. ER probe corrosion rate for JB6.

Date	Corr Rate (mpy)
10/25/2010	0.00
10/26/2010	0.00
10/27/2010	0.00
10/28/2010	0.00
10/29/2010	1.21
11/29/2010	2.03
12/20/2010	1.26
1/26/2011	1.42
2/22/2011	1.10
3/29/2011	1.06
4/19/2011	1.00
5/18/2011	0.91
6/16/2011	0.94
7/19/2011	0.82
8/12/2011	0.80
Average	0.84

Figure 38. ER corrosion rate versus time for JB6 in native-soil backfill with no CP.

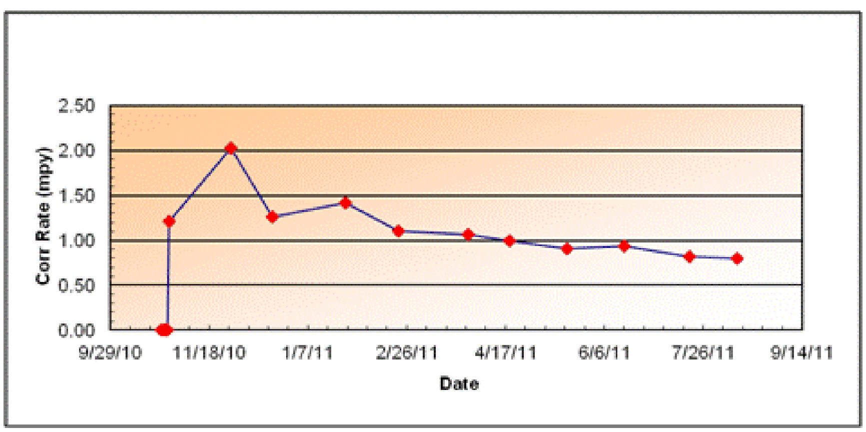
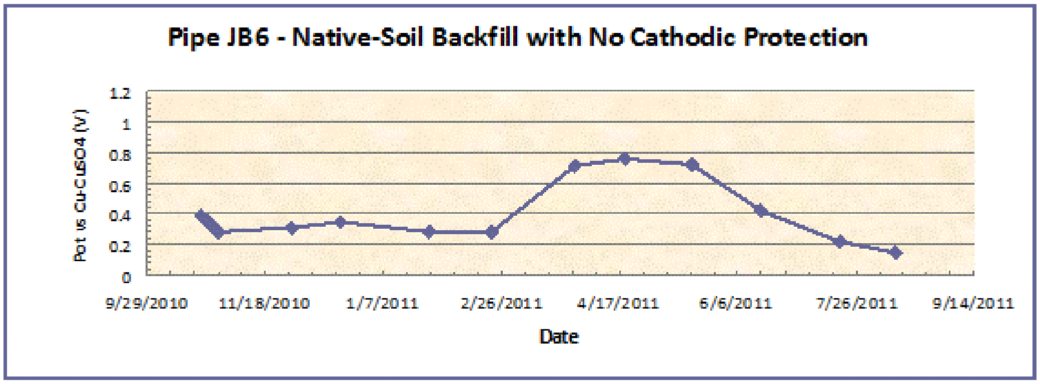


Figure 39. Free corrosion potential of JB6 versus $Cu/CuSO_4$ reference electrode over time in native-soil backfill.



3.2.7 Summary of corrosion data

Figure 40 – Figure 42 and Table 18 show the corrosion data results from the field demonstration. The data from the sections with and without CP are shown separately in each figure. Figure 40 shows a direct comparison of the corrosion rate of each pipe segment as measured by LPR over time. Figure 41 compares the same pipe segments as measured by ER. Figure 42a shows the minimum CP protection level for each section and Figure 42b shows the free corrosion potential versus a Cu/CuSO4 reference electrode over time for the pipe sections that were not cathodically protected.

Figure 40. LPR corrosion rate versus time for individual pipe sections with CP (a) and without CP (b).

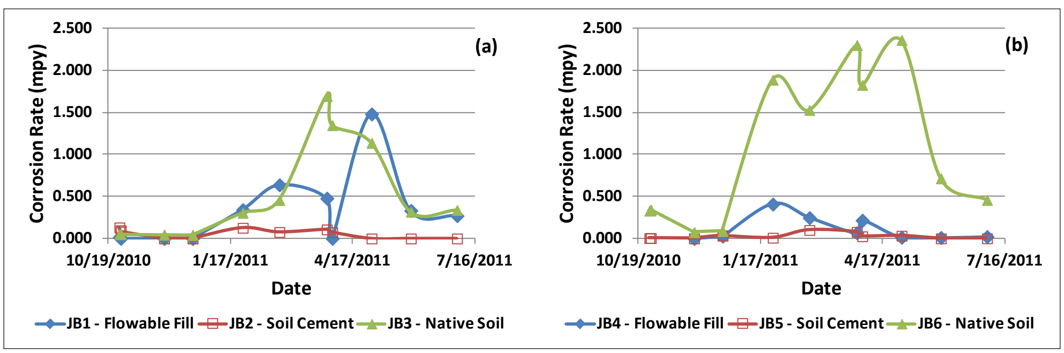


Figure 41. ER corrosion rate versus time for individual pipe sections with CP (a) and without CP (b).

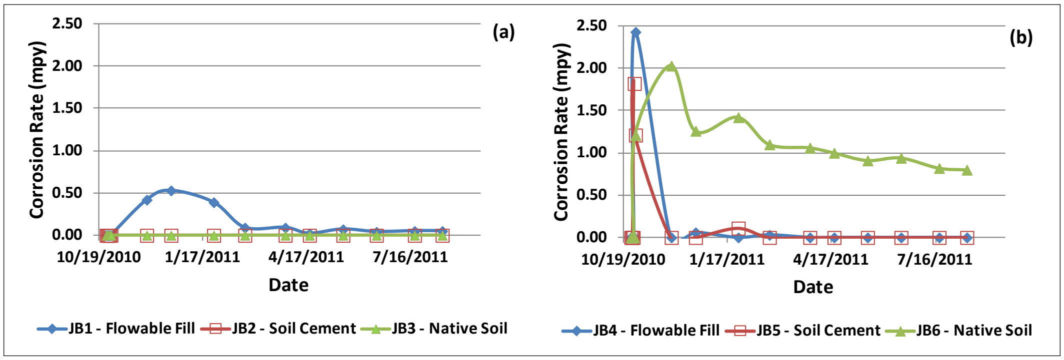


Figure 42. Anode current output and instant-off potential of cathodically protected pipe segments versus $Cu/CuSO_4$ reference electrode (a) and free corrosion potential over time for individual pipe sections versus $Cu/CuSO_4$ reference electrode (b).

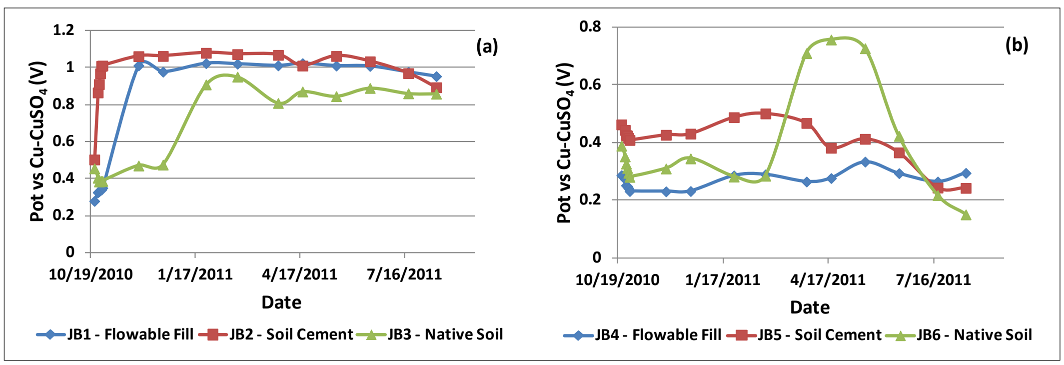


Table 18. Corrosion data summary.

Pipe Section	Fill	Avg. LPR Corr Rate (mpy)	Avg. ER Corr Rate (mpy)	Cathodic Protection	Average CP Current (mA)
JB1	Flowable fill	0.255	1.90 / 0.12*	Yes	7.500
JB2	Soil Cement	0.050	0.00	Yes	4.875
JB3	Native Soil	0.422	0.00	Yes	13.313
JB4	Flowable fill	0.095	0.17	No	N/A
JB5	Soil Cement	0.024	0.21	No	N/A
JB6	Native Soil	0.886	0.84	No	N/A

*Corrected for outlier data as described in the text.

The average LPR corrosion rates were the highest in native soil fill (0.422 – 0.866 mpy). In native soil without CP (JB6), there was very good agreement between the average LPR and ER corrosion rates (0.886 and 0.84 mpy). With CP, corrosion in native soil was completely arrested. The average LPR corrosion rates in soil cement were lower (0.024 – 0.050 mpy) than those in flowable-fill (0.095 – 0.255 mpy), and both of these were lower than the average LPR corrosion rates in native soil (0.422 – 0.866 mpy).

The LPR and ER corrosion rates did not completely agree with each other, as expected, because LPR measurements are altered by CP current flow, which distorts the analysis. Under these conditions, the LPR methodology is usually not accurate. Comparisons and correlations are generally even more difficult where corrosion rates are low. Furthermore, the measurements cannot be directly compared at all where ER probes are under CP and LPR probes are not. The average ER-measured corrosion rate in soil cement with CP was zero, as would be expected. Without CP, the average ER corrosion rate in soil cement was 0.21 mpy while the corresponding LPR corrosion rate was almost 10 times lower (0.024 mpy). In flowable fill without CP, the average LPR and ER corrosion rates were 0.095 mpy and 0.17 mpy, respectively.

The actual average ER corrosion rate measured in flowable fill under CP (JB1) was 1.90 mpy. It should have been zero under CP, but three of the data points are inconsistent with the rest of the data as can be seen in Figure 41a. These outlier data points probably resulted from transitory ER instrument errors, and can reasonably be ignored. If these three points are excluded, the average ER corrosion rate decreases to 0.12 mpy, as reported in Table 18, which indicates a rate that would be considered reasonable under CP in an alkaline environment.

The high initial corrosion rates measured by the ER probes in Figure 41b are not surprising. In a corrosive environment, corrosion of steel begins at a high rate until a passivating film forms and stabilizes, which acts to reduce the corrosion rate toward zero. This effect did not occur for specimen JB6, which was buried in native soil with no cathodic protection.

The average CP current in soil cement and flowable fill was reduced by about 63% and about 44%, respectively, compared with the requirement for pipes in native soil. The average CP current in soil cement was about 35% lower than that in flowable fill. For the specimens without CP, Figure 42b shows typical free corrosion potentials on the order of 0.250–0.500 V compared with the Cu/CuSO4 reference electrode. These measurements are indicative of steel passivated by alkaline flowable fill.

3.3 Lessons learned

3.3.1 Soil chemistry

The site selection for a test of this type is very important to ensure that the native soil to be used in the soil cement is compatible with the corrosion-prevention objective. Soil testing performed after the project began found that the native soil was not capable of producing a soil cement due to its fine silt and clay composition. This then required that testing and evaluation be conducted to experiment with additives for amending the soil and cement mixture to achieve a satisfactory soil cement for use in this evaluation. Once the mix design was completed, the soil cement had to be produced by a cement company for use in this demonstration.

3.3.2 Application

Both flowable fill and soil cement were capable of completely mitigating all corrosion on the bare metal surfaces of the LPR probes, ER probes, and bare metal pipe surfaces where they were in direct contact with the demonstrated fills.

The use of flowable fill or soil cement requires training and understanding of the technology differences, both with respect to preparing the CLSM and the delivery and placement of the materials. The following considerations should be observed:

- Hire mix companies that are familiar with the process and operate trucks that are compatible with it. Alternately, negotiate terms with companies that are willing to be trained in the requirements of using these materials. The use of flowable fill requires only minor changes to normal mix and delivery practices. However, the use of soil cement requires that the existing soil first be graded and found suitable for use. This may require screening to remove oversize stones, and attention must be given to mix with cement and water in an appropriately sized system.
- Proper trenching and bedding of the pipe before placement of either flowable fill material is essential to assure complete encapsulation of the pipe (minimum of 4 – 6 in. on all sides) for long-term corrosion protection by passivation.
- Pipe supports installed to assure 4 – 6 in. clearance under the pipe before placement of the fill must be electrochemically compatible with

the fill material along the entire pipe and any applied cathodic protection current in order to avoid corrosion "hot spots" seen on most pipe specimens in this project.

To elaborate on the third item above, the support pads in future applications, measuring 4 – 6 in. clearance as needed, must be filled dry with flowable fill consisting of 100 lb Portland cement per cubic yard of sand, then wetted just before placing of the pipe on the bags so that the support pads can conform to the shape of the pipe.

In the case of the pipe specimen buried in flowable fill and protected by CP, the incorrectly prepared support pads did not interfere with the corrosion protection. However, the CP-protected specimen buried in soil cement was not completely free of corrosion where the improperly prepared support pads were in contact with the steel.

Both the flowable fill and soil cement materials could be placed like standard concrete, but no compaction or vibration was necessary to achieve maximum consolidation and distribution of either. After being poured into the trench, the materials settled and self-leveled without any further effort by the construction crew.

Placement of the material was as simple as pouring concrete to the desired depth of cover. After 8–12 hours, when the material reached its initial set condition, the remainder of the trench could be backfilled with native soil.

It is noted that pouring CLSMs on steep grades may require multiple pours or special cofferdams to prevent the material from flowing downhill, even though this issue was not encountered during the demonstration.

3.3.3 Operational issues

The increased bearing capacities of flowable fill and soil cement compared to native soil at the demonstration site may reduce or eliminate the need to use thrust blocks and joint restraints in many applications.

Although pipe installed in cured flowable fill or soil cement will be difficult to excavate by hand, excavation is easily accomplished using a backhoe.

4 Economic Analysis

4.1 Costs and assumptions

This project was a field investigation intended to determine whether flowable fills have effective corrosion-mitigation properties that can enhance the effectiveness of cathodic protection and/or reduce CP current requirements. Demonstration cost figures and data were recorded to offer a basis for return-on-investment projections. It is likely that costs for real-world applications could be reduced by applying the lessons learned discussed in section 3.3, but this analysis is based only on project data.

Baseline Case. The return on investment (ROI) analysis in this study compares the costs of the demonstration scenario with that of the standard practice of performing maintenance on existing pipes that were installed without any protection, which was not uncommon in the past. For the sake of this analysis, this cost of maintenance and potential pipe replacement is assumed to be $2.2 million once every 10 years.

Demonstrated Technology. The calculations use $500,000 as the total investment of the flowable fill corrosion-protection capability. This cost would cover design, installation, equipment and maintenance of an impressed-current cathodic protection system used in conjunction with flowable fill, but does not include existing pipe-burying utility construction. This additional investment in corrosion-prevention technology is slightly more than 20% the original cost of the retrofit, and is higher than a conservative estimate in practice. The material costs for the demonstration were approximately $25,000 (see Appendix C), with an additional $5,000 for excavation and $1,000 for CLSM blending and delivery. This material list is specific to the requirements of the subject demonstration, including testing equipment, but a full-scale application should not need the research-related items used in this project.

The maintenance requirements for flowable fills are minimal. If left undisturbed, either system should provide corrosion protection indefinitely. However, to provide a conservative economic analysis, a minimal yearly inspection cost of $2,000 is included in the calculation. It is expected that settling of soil, damage from nearby excavations, or similar disturbances may lead to significant repair expenses every 10 years, on average, so this cost is also accounted for in the calculation at Years 10, 20, and 30.

4.2 Projected return on investment (ROI)

Using methods prescribed in Office of Management and Budget Circular No. A-94, the ROI ratio for this demonstration project is projected to be 3.89 over 30 years. The calculations are shown in Table 19.

Table 19. Return on investment calculation.

Return on Investment Calculation

Investment Required			**500,000**
Return on Investment Ratio	**3.89**	**Percent**	**389%**
Net Present Value of Costs and Benefits/Savings	**31,929**	**1,975,820**	**1,943,891**

A Future Year	B Baseline Costs	C Baseline Benefits/Savings	D New System Costs	E New System Benefits/Savings	F Present Value of Costs	G Present Value of Savings	H Total Present Value
1							
2		2,000			1,747		-1,747
3		2,000			1,633		-1,633
4		2,000			1,526		-1,526
5		2,000			1,426		-1,426
6		2,000			1,333		-1,333
7		2,000			1,245		-1,245
8		2,000			1,164		-1,164
9		2,000			1,088		-1,088
10	2,200,000	12,000			6,100	1,118,260	1,112,160
11		2,000			950		-950
12		2,000			888		-888
13		2,000			830		-830
14		2,000			776		-776
15		2,000			725		-725
16		2,000			677		-677
17		2,000			633		-633
18		2,000			592		-592
19		2,000			553		-553
20	2,200,000	12,000			3,101	568,480	565,379
21		2,000			483		-483
22		2,000			451		-451
23		2,000			422		-422
24		2,000			394		-394
25		2,000			368		-368
26		2,000			344		-344
27		2,000			322		-322
28		2,000			301		-301
29		2,000			281		-281
30	2,200,000	12,000			1,577	289,080	287,503

5 Conclusions and Recommendations

5.1 Conclusions

Data collected during this project indicate that the flowable fill with proprietary admixture as used with cathodic protection can effectively mitigate corrosion of buried bare steel pipe. The demonstrated soil cement CLSM used with CP returned a similar result except at isolated locations on specimens in which pipe-support pads were mistakenly backfilled with native soil instead of the soil cement. Similar isolated corrosion activity was noted for both types of CLSM where specimens were not protected by CP and pipe-support pads were improperly prepared. These isolated problems are addressed below in section 5.2.1.

An important benefit observed for both CLSMs was the reduction in cathodic protection requirements where either fill material was used. This reflects the corrosion-control properties inherent in these alkaline, cementitious materials. Specifically, the average CP current required for corrosion protection in soil cement and flowable fill specimens was reduced by about 63% and about 44%, respectively, compared with the requirement for the protected pipe in native soil. The average CP current requirement in soil cement was about 34% lower than in flowable fill. Cathodic protection also provided supplemental corrosion reduction where the incorrectly filled support pads were installed. Thus, with proper installation, similar reductions in CP current requirements might be realized as cost savings by reducing the number or size of galvanic anodes needed to provide complete corrosion protection with flowable fill or soil cement. It is also reasonable to assume that pipe installed with a properly specified coating system would further reduce the CP current requirements when buried in either flowable fill material.

5.2 Recommendations

5.2.1 Applicability

Flowable fill may be used with virtually any buried ferrous structure that needs corrosion protection. Soil cement also may be used for such applications in locations where the native soil has compatible electrochemical and mechanical properties.

Because isolated corrosion did occur using both CLSMs due to installer error, as explained in sections 3.2 and 5.1, some caveats apply. Since it is not possible to completely eliminate installer error or to guarantee 100% efficacy of CLSM blending or placement, the application of an appropriately sized and designed cathodic protection system would provide the most conservative engineering approach. Demonstration results strongly indicate that either demonstrated CLSM would greatly reduce the CP requirement as compared with the same pipe material buried only in native soil.

Both of the demonstrated materials have the added benefit of providing 100% encapsulation of the structure within a very stable environment. Therefore, it is considered highly applicable to new construction of buried ductile and gray cast iron pipe, steel pipe, underground storage tanks, H-piles in disturbed earth, etc. Also, for coated pipe in expansive clay soils, either of the demonstrated fill materials provides mechanical protection for the coating, which may otherwise be damaged by soil expansion and contraction.

The results of this demonstration should not be understood to imply that CLSMs are recommended for use with buried aluminum structures; high-pH environments can potentially disrupt the naturally forming adherent oxide scale layer that itself protects aluminum. Therefore, CLSMs should not be assumed to be compatible with aluminum without a full engineering analysis of the structure and site.

5.2.2 Implementation

It is recommended that the implementation of CLSMs for protecting underground piping structures from corrosion be specified through inclusion in two Unified Facilities Guide Specifications (UFGS):

- UFGS-26 42.1400 10 (Cathodic Protection System [Sacrificial Anode])
- UFGS-26 42.1700 10 (Cathodic Protection System [Impressed Current])

Revisions to these specifications should include caveats that prohibit using CLSMs in conjunction with coke breeze and other conductive fills around the anode beds. Also, the specifications should clearly indicate that CLSMs are intended for use with—not in place of—cathodic protection.

It is recommended that electrical resistance (ER) probes be used in full-scale applications on critical pipelines: they provide an easy and inexpensive means of monitoring corrosion rates as well as CP effectiveness.

5.2.3 Follow-on field validation

A demonstration study using full-scale pipe sections and CLSMs could be designed to provide a direct and controlled comparison of corrosion performance, and life-cycle costs versus native soil backfill and standard cut-and-fill methods. (Such comparisons could not be considered complete in the context of the small scale of the experimental project reported here.) For example, a test section approximately 50% of the overall length of a selected pipe structure could be encased in a CLSM and electrically isolated from the other half, with CP current flows to both sections monitored over time. Experimental control would be provided by comparing CP current requirements and polarization data for the other half of the structure that is buried in native soil.

A research problem to be considered in a follow-on study would be evaluating the impact of different soil types and resistivities in conjunction with CLSMs. The purpose would be to determine the degree to which native soils with much lower resistivity than the standard flowable fill might effectively shield the pipe structure from protective current (i.e., reducing protection). Results could, hypothetically, require guidance about designing CLSM resistivity properties for some applications.

Another recommendation for the follow-on study is to include calculations for use in developing a reference table summarizing pipe dimensions in terms of buoyancy when buried in various CLSM compositions. This tool would help to determine cases where larger pipes would need to be weighted down to provide negative buoyancy against the liquid fill material during pouring and curing phases. Without such a tool, larger-diameter piping could tend to float to the top of the trench during fill operations.

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Appendix A: Flowable Fill and Soil Cement Mix Design

Flowable fill

Rone Engineering

8908 Ambassador Row, Dallas, TX 75247
4221 Freidrich Lane, Suite 195, Austin, TX 78744
7701 W. Little York, Suite 600, Houston, TX 77040
Corporate Phone: (214) 630-9745

CONFIRMATION MIX #TM 2000
FLOWABLE FILL

Client: Mandaree
Attn: Karl Palutke
812 Park Drive
Warner Robins, GA 31088

Project No.: 10-16279
Date: 9/28/2010
Report No.: TM 2000
Page 1 of 1

Project: Fort Hood
Sand Cement Design

Requirements

Minimum Compressive Strength:	50 psi @ 7 days
Minimum Compressive Strength:	100 psi @ 7 days
Water Cement Ratio:	1.50 lb water/lb cement
Air Content:	20.0 %
Slump (inches):	9.0 inches
Minimum Cement Content:	2.0 sack

Materials

Type	Description	Specific Gravity	Unit Weight (lb/cubic ft)	Solids (%)
Cement (ASTM C-150)	Type I/II	3.15	94.0	47.8
Fly Ash		2.70	0.0	0.0
Coarse Aggregate (ASTM C-33)		2.64	0.0	0.0
3/8" Pea Gravel		2.63	0.0	0.0
Fine Aggregate	Transit Mix	2.63	108.5	66.1
Water	Potable Water	1.00	62.4	100.0
Admixture #1	DaraFill			

2.0 Sack Sand Cement

	Quantities	Absolute Volume
Cement:	188 lb	0.96 cubic feet
Fly Ash	0 lb	0.00 cubic feet
Coarse Aggregate:	0 lb	0.00 cubic feet
3/8" Pea Gravel	0 lb	0.00 cubic feet
Fine Aggregate	2646 lb	16.12 cubic feet
Water	282 lb	4.52 cubic feet
Admixture #1(ASTM C-260):	0.4 lbs	5.40 cubic feet
Water Cement Ratio:	1.50 lb water/lb cement	
Unit Weight:	115.4 lb/cubic ft	27.00 cubic feet

Rone Engineering Services, Ltd.

Lawrence Bracken
Vice President

* Correct for Free Moisture and/or Absorption
Remarks: Volume in Above are Absolute unless otherwise noted.
Water added at mixer must include the liquid of the Admixtures.

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Soil cement

Rone Engineering

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4221 Freidrich Lane, Suite 195, Austin, TX 78744
7701 W. Little York, Suite 600, Houston, TX 77040
Corporate Phone: (214) 630-9745

CONFIRMATION MIX #2500A

SOIL CEMENT

Client: Mandaree
Attn: Karl Palutke
812 Park Drive
Warner Robins, GA 31088

Project No.: 10-16279
Date: 9/28/2010
Report No.: 2500A
Page 1 of 1

Project: Fort Hood
Soil Cement Design

Requirements

Minimum Compressive Strength:	50	psi @ 7 days
Minimum Compressive Strength:	100	psi @ 7 days
Water Cement Ratio:	3.00	lb water/lb cement
Air Content:	20.0	%
Slump (inches):	9.0	inches
Minimum Cement Content:	2.5	sack

Materials

Type	Description	Specific Gravity	Unit Weight (lb/cubic ft)	Solids (%)
Cement (ASTM C-150)	Type I/II	3.15	94.0	47.8
Fly Ash		2.70	0.0	0.0
Coarse Aggregate (ASTM C-33)		2.64	0.0	0.0
3/8" Pea Gravel		2.63	0.0	0.0
Natural Soil	Fort Hood, TX	2.55	98.0	61.6
Water	Potable Water	1.00	62.4	100.0
Admixture #1	DaraFill			

2.5 Sack Soil Cement

	Quantities		Absolute Volume	
Cement:	235	lb	1.20	cubic feet
Fly Ash	0	lb	0.00	cubic feet
Coarse Aggregate:	0	lb	0.00	cubic feet
3/8" Pea Gravel	0	lb	0.00	cubic feet
Natural Soil	1449	lb	9.11	cubic feet
Water	705	lb	11.30	cubic feet
Admixture #1(ASTM C-260):	0.4	lbs	5.40	cubic feet
Water Cement Ratio:	3.00	lb water/lb cement		
Unit Weight:	88.5	lb/cubic ft	27.00	cubic feet

Rone Engineering Services, Ltd.

* Correct for Free Moisture and/or Absorption

Remarks: Volume in Above are Absolute unless otherwise noted.
Water added at mixer must include the liquid of the Admixtures.

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approval of the testing laboratory. The use of our name must receive written approval. Our lett
and/or inspected, and are not indicative of the quantities of apparently ider

Appendix B: Fill Compressive Test Results

Flowable fill compressive test

Rone Engineering

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4421 Freidrich, Ste 195, Austin, TX 78744
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Report of Flowable Fill Compressive Strength Test

Client: Mandaree Enterprises Corporation
812 Park Drive
Warner Robins, GA 31088

Report No.: 518724
Project No.: 1016279
Date of Service: 10/20/2010
Report Date: 10/28/2010

Project: Fort Hood DPW - PO# 2010-033

Services: Obtain samples of fresh flowable fill at the placement locations, perform required testing, cast compressive strength samples and bring samples back to the laboratory for curing and testing in accordance with applicable standards.

PROJECT DATA

Contractor:
Concrete Supplier: Transit
Plant: NA
Specification Requirements
Strength: 100 psi @ 7 days
Slump (in.): 9" maximum
Air (%): 20% - 30%
Test Method: ASTM C-172
ASTM C-31 (except 10.1.2)
ASTM C-143
ASTM C-231
ASTM C-1064
ASTM C-138
ASTM C-39

Mix Design I.D.: 9996
Placement Date: 10/20/2010
Weather Conditions: Clear
Time Sampled: 03:00pm **Batch time:** 02:41pm
Temperature - Air: 85ºF **Concrete:** 83ºF
Truck No: 7009 **Ticket No:** 2202911
Air Content: 0.7% **Unit Weight (pcf):** NA
Overall Placement Location:
Test holes #2 and #5

Sample Location:
same as above

Measured Slump (inches) 11.75

REPORT OF TESTS

Concrete Compressive Cylinder 3" x 6"

Cylinder Marked Set	Cylinder Marked No.	Date Tested	Age (days)	Diameter (in)	Area (in²)	Maximum Load (lbs)	Compressive Strength (psi)	Fracture Type
1	1	10/25/2010	5	3.00	7.07	680	100	Type 2
1	2	10/27/2010	7	3.01	7.12	680	100	Type 5
1	3	11/17/2010	28					
1	4	11/17/2010	28					
1	5	**HOLD**						
1	6	**HOLD**						
1	7	**HOLD**						

LIMITATIONS: The test results presented herein were prepared based upon the specific samples provided for testing. We assume no responsibility for variation in quality (composition, appearance, etc.) or any other feature of similar subject matter provided by persons or conditions over which we have no control. Our letters and reports are for the exclusive use of the clients to whom they are addressed and shall not be reproduced except in full without the written approval of Rone Engineering Services, Ltd. (KW/KW)

Page 1 of 2

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Report of Flowable Fill Compressive Strength Test

Client: Mandaree Enterprises Corporation
812 Park Drive
Warner Robins, GA 31088

Report No.: 518724
Project No.: 1016279
Date of Service: 10/20/2010
Report Date: 10/28/2010

Project: Fort Hood DPW - PO# 2010-033

Services: Obtain samples of fresh flowable fill at the placement locations, perform required testing, cast compressive strength samples and bring samples back to the laboratory for curing and testing in accordance with applicable standards.

REPORT OF TESTS

Concrete Compressive Cylinder 3" x 6"

Cylinder Marked		Date	Age	Diameter	Area	Maximum Load	Compressive Strength	Fracture
Set	No.	Tested	(days)	(in)	(in²)	(lbs)	(psi)	Type
1	8	HOLD						

Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Remarks: 50-100 psi at 7 days
pH = 12

Technician: Jarrod Miller

See Report 518722 for technician time

Report Distribution:
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Attn: Mr. Karl Palutke (1-ec copy)
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Attn: Mr. K. Scott Watson
1-ec Mandaree Enterprises Corporation Attn: Mr. Dave Butler

Rone Engineering

K. Scott Watson, AET
Project Manager

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Soil cement compressive test

Rone Engineering

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Corporate Phone: (214) 630-9745

Report of Flowable Fill Compressive Strength Test

Client: Mandaree Enterprises Corporation
812 Park Drive
Warner Robins, GA 31088

Report No.: 518722
Project No.: 1016279
Date of Service: 10/20/2010
Report Date: 10/28/2010

Project: Fort Hood DPW - PO# 2010-033

Services: Obtain samples of fresh flowable fill at the placement locations, perform required testing, cast compressive strength samples and bring samples back to the laboratory for curing and testing in accordance with applicable standards.

PROJECT DATA

Contractor:
Concrete Supplier: Sand mix
Plant: NA
Specification Requirements
Strength: 100 psi @ 7 days
Slump (in.): 9" maximum
Air (%): 20% - 30%
Test Method: ASTM C-172
ASTM C-31 (except 10.1.2)
ASTM C-143
ASTM C-231
ASTM C-1064
ASTM C-138
ASTM C-39

Mix Design I.D.: 9998
Placement Date: 10/20/2010
Weather Conditions: Clear
Time Sampled: 02:50pm **Batch time:** 02:05pm
Temperature - Air: 85ºF **Concrete:** 83ºF
Truck No: 9003 **Ticket No:** 2202860
Air Content: 23.0% **Unit Weight (pcf):** NA
Overall Placement Location:
Test holes #1 and #4

Sample Location:
Same as above

Measured Slump (inches)
9.75

REPORT OF TESTS

Concrete Compressive Cylinder 3" x 6"

Cylinder Marked Set	Cylinder Marked No.	Date Tested	Age (days)	Diameter (in)	Area (in²)	Maximum Load (lbs)	Compressive Strength (psi)	Fracture Type
1	1	10/25/2010	5	3.01	7.12	510	70	Type 2
1	2	10/27/2010	7	2.99	7.02	850	120	Type 2
1	3	11/17/2010	28					
1	4	11/17/2010	28					
1	5	**HOLD**						
1	6	**HOLD**						
1	7	**HOLD**						

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Corporate Phone: (214) 630-9745

Report of Flowable Fill Compressive Strength Test

Client: Mandaree Enterprises Corporation
812 Park Drive
Warner Robins, GA 31088

Report No.: 518722
Project No.: 1016279
Date of Service: 10/20/2010
Report Date: 10/28/2010

Project: Fort Hood DPW - PO# 2010-033

Services: Obtain samples of fresh flowable fill at the placement locations, perform required testing, cast compressive strength samples and bring samples back to the laboratory for curing and testing in accordance with applicable standards.

REPORT OF TESTS

Concrete Compressive Cylinder 3" x 6"

Cylinder Marked		Date Tested	Age (days)	Diameter (in)	Area (in²)	Maximum Load (lbs)	Compressive Strength (psi)	Fracture Type
Set	No.							
1	8	HOLD						

Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Remarks: 50-100 psi @ 7 days
pH = 11

Technician: Jarrod Miller **Started:** 12:30pm **Finished:** 06:00pm

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Attn: Mr. K. Scott Watson
1-ec Mandaree Enterprises Corporation Attn: Mr. Dave Butler

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Project Manager

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Appendix C: Fort Hood Demonstration Equipment and Materials for ROI Analysis

Materials / Supplies	Description	Vendor	Qty	Amount
Gamry Equipment	Reference 600 Potentiostat/Galvanostat/ZRA (992-00056)	Gamry	1	$9,350
Corrosion Rate Probes	LPR probes with (3) carbon steel tips 10 mm dia x 29.3 mm long, plus (3) stainless steel 10-32 threaded rods and nuts	Metal Samples	9	$3,119
Gamry Software	DC105 DC Corrosion Technique Software License	Gamry	1	$2,385
Pipe	10 ft long x 6 in. diameter, zero welds, min 0.188 in. wall thickness	SK Construction	6	$2,021
ER Meter	Model MS 1500E	Metal Samples	1	$1,945
Test Stations	12 in. (w) x 12 in (h) x 6 in. (d) galvanized box w/phenolic board mounted 1.5 in offset/ 2 hole mount center connected	JA Elect	6	$1,929
ER Probes	Model ER0500/ carbon steel elements 40/50 mills	Metal Samples	3	$930
Zinc anodes	1.4 in. x 1.4 in. x 30 in. Galvotec Model GA-S-18 with 20 ft. of #12 AWG THNN solid anode wire (red)	Allied	9	$726
Blast material	50 lb. bags (Black Beauty) or equiv. / 60 ft. of 6 in.	SK Construction	as needed	$660
Pipe pit depth guage		Albuquerque	1	$355
Mass Loss probe		ATS		$330
Wiring Harness		Gamry	1	$300
Safety Sinage		Signs Now	6	$231
Epoxy gun	For SPC 2888 tubes	Allied	1	$195
Soil box	Agra	Allied	1	$140
Epoxy	SPC 2888	Allied	3	$114
Auger rental	Trench digging	RCS	1	$75
Resistor	rheostat type	JA Elect	3	$68
Shunt	0.1 ohm	JA Elect	3	$53
Fittings	toggle switch	JA Elect	3	$53
Fence posts	4 in. x 4 in. x 6 ft.tall treated posts	Lowes	6	$28
Wire	#18 Thnn stranded yellow, green, blue	Dealers Electric	75 ft. each	$73
Fittings	PVC 2 in. plugs	HD/Lowes	10	$19
Duct Tape	standard 4 in.	Dealers Electric	2	$15
pH paper	Ph- paper with 1-Ph unit precision	Ph Ion Diagnostic	6	$13
Acetone	acetone de-greaser	Lowes	1 qt.	$7
PVC	1.25 in. for electrical	Dealers Electric	20 ft.	$5
Fittings	PVC 2 in. sleave	HD/Lowes	5	$4
			Total	**$25,143**

Note: Vendors are listed only for informational purposes related to the demonstration without implying any endorsement by the Department of Defense.

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December 2015	Final	

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5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Scott M. Lux, Charles P. Marsh, James B. Bushman, Bopinder S. Phull, Christopher Olaes, and Larry Clark

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Washington, DC 20301-3090

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
Researchers investigated the use of controlled low-strength materials (CLSMs) to reduce the corrosion rate of buried steel structures. These thin, self-consolidating cementitious materials, also called "flowable fills," have an alkaline chemistry that could promote rapid passivation of buried steel surfaces. Two different CLSM blends were tested. Both used cement and a flowability admixture, but one used native soil instead of standard fine aggregate. Using six prepared bare steel pipe specimens, six pipe beds were prepared to evaluate the corrosion-mitigation effects of the two CLSMs used both with and without galvanic cathodic protection (CP). Two control specimens were backfilled using native soil, with and without CP. Commercial probes and instrumentation were used to monitor the specimens for 13 months, logging linear polarization resistance and electrical resistance data for post-exposure evaluation. After excavation, the specimens were also visually inspected for corrosion effects. Results indicated that both flowable fill materials, as used with CP, can effectively mitigate corrosion. Isolated corrosion cells formed where the pipe support pads for the soil cement specimens were improperly installed, resembling isolated corrosion that also appeared on flowable fill specimens without CP. The calculated return on investment for this project was 3.89.

15. SUBJECT TERMS
corrosion mitigation; flowable fill materials; controlled low-strength materials (CLSM); cathodic protection; buried steel pipes

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