Compatibility Evaluation of Groundwater Cutoff Wall Using Salt-Resistant Bentonite and BFS/Cement for Deep-Mix Barrier Wall

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ABSTRACT

A former sludge disposal basin at a Superfund site in Colorado requires the installation of a vertical deep mixing groundwater cutoff wall as a part of the overall site remediation. This barrier wall will be approximately 8,030 square meters and will prevent the flow of groundwater through the contaminated soil. The barrier wall will extend to a low permeability layer at 13.7 meters below ground surface (bgs). Soil mixing was selected based on consideration of cost, less exposure of the highly odorous waste material at the surface, and elimination of off-site disposal of waste soil.

A bench scale compatibility study was performed using onsite soils and groundwater for a leachate to evaluate the impacts of the on-site contaminants to the performance and constructability of the soil mixing. This paper discusses the process for designing the study, selection of test parameters, selection of appropriate low-permeability reagents used in the testing, and the test results.

In order to obtain a low permeability barrier wall ($\leq 1x10^{-7}$ cm/sec), several slurries were created and subjected to initial compatibility testing. Acceptable slurries were then made with the groundwater and long-term hydraulic conductivity tests were set up for two different mixtures (soil-bentonite and soil-cement). The reagents used in each mixture were:

- Soil-Bentonite: SW101(salt-resistant bentonite)/lignosulfate thinner
- Soil-Cement: Blast furnace slag/Portland Cement I-II/bentonite/soda ash

The ratios were set for each of these reagent materials to meet the required permeability while still providing a flowable slurry or grout for deep soil mixing. The test results indicate that the optimum mixture, based on cost and the lowest permeability, is the soil-bentonite mix.

INTRODUCTION

The site is located at the Rocky Mountain Arsenal (RMA) in southern Adams County, Colorado, approximately 16 kilometers northeast of downtown Denver. The Section 36 Lime Basins (LB) site was used to precipitate metals from aqueous waste from the production of chemical weapons, herbicides and pesticides. The basins ceased to be used in 1975, and were filled in with cover soil. The on-site groundwater is highly alkaline and contaminated with volatile organic compounds (primarily chloroform and organochlorine pesticides) and arsenic. The contaminated soil in the basins is considered an additional contributor to groundwater contamination at the RMA.

Due to the odorous nature of the contaminated soil and material handling concerns, the selected remedy for the site is on-site containment and requires placement of a vertical groundwater barrier wall around the deeper waste soil and construction of a RCRA-equivalent soil cover over the entire project area. In order to avoid the problems of odor and additional waste disposal associated with slurry wall techniques, deep soil mixing with augers was chosen for barrier construction. In addition, a series of groundwater dewatering wells will be installed within the containment area to create an inward gradient (see Figure 1). Extracted groundwater will be treated at an on-site CERCLA wastewater treatment facility prior to reintroduction into the groundwater table (gwt) downstream from the site.

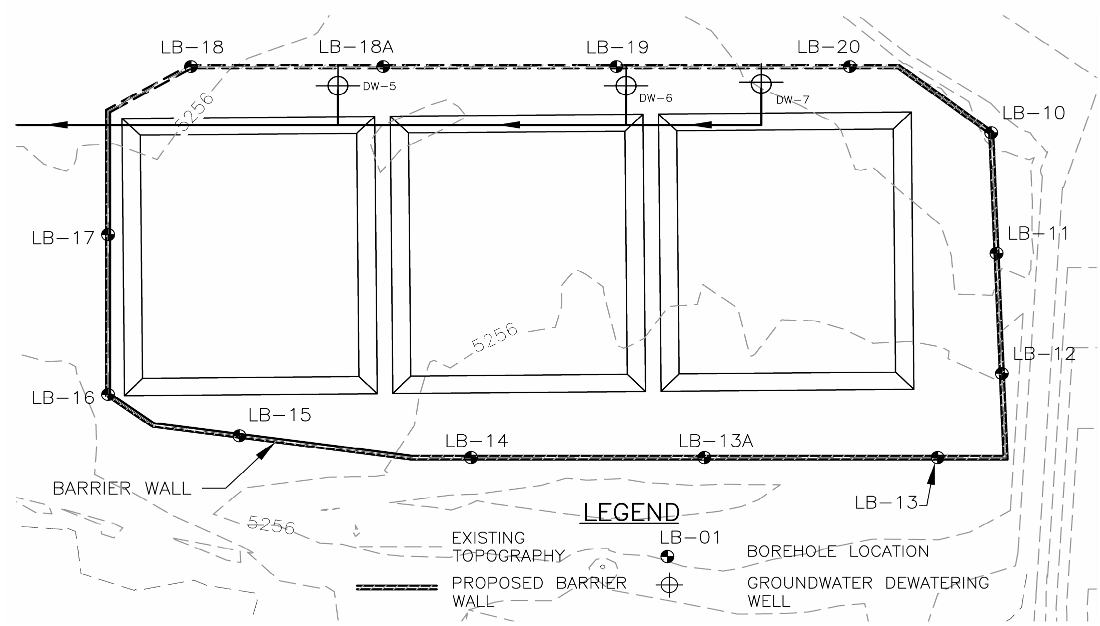

Figure 1. Site Plan View

STUDY OBJECTIVES

One of the project goals is to key the vertical barrier wall into a soil formation or bedrock with a similar hydraulic conductivity as the barrier wall to minimize leakage under the wall. In order to find an optimum blend of native soil and reagents in slurry to create a low hydraulic conductivity barrier wall a bench scale compatibility study was performed. The compatibility study includes the geotechnical evaluation of the existing soil along the proposed alignment of the barrier wall, chemical analysis of the existing groundwater from the site, and compatibility testing of both the potential slurries and soil/slurry mixtures. In this respect, “compatibility” refers to both the hydraulic conductivity and durability of the barrier wall material when exposed to the contaminated groundwater or permeant. Predetermining the compatibility of slurry/barrier wall materials with contaminated groundwater is generally recognized as good engineering practice (Ryan 1987; Day 1994). Compatibility tests should simulate the long-term, worst case performance of barrier walls in a contaminated groundwater environment (Day 1994).

DESIGN INVESTIGATIONS

A field investigation soil boring program was performed, prior to laboratory testing, to gather further information for development of the barrier wall. This investigation determined the depth to competent bedrock along the centerline of the proposed wall alignment and appropriate geotechnical properties of the soil. In order to locate buried objects in the work area, an electromagnetic geophysical survey was performed to aid in barrier wall alignment selection. The results of this geophysical survey allowed the proposed alignment of the barrier wall to avoid both known objects and geophysical anomalies. Record drawings of the basins were also consulted to identify known non-ferrous objects buried at the site.

A split-spoon sampler was used to collect soil samples from each augered borehole for geotechnical analysis, and packer tests were performed in several of the drilled core holes within the bedrock. From borehole log information the site stratigraphy consisted of alluvium from 4.6 to 7.6 meters bgs, underlain by weathered bedrock down to approximately 13.7 meters bgs, and a zone of competent bedrock at 13.7 meters bgs. The soil types identified above the bedrock were CH, CL, SC, SM-SC, and SM, with most of the soil classified into the CL category. The moisture contents generally ranged from 7% to 12% above the gwt, and from 19% to 33% below the gwt. Packer test results in the competent bedrock indicated a hydraulic conductivity varying from 1.2×10^{-7} to 6.1×10^{-7} cm/sec.

COMPATIBILITY STUDY

The bench scale testing plan consisted of four parts conducted sequentially. The first part involved determination of the design permeant for the testing, and the subsequent three (referred to as Tiers I, II and III) involved development and testing of the candidate slurries and mixtures of these slurries with site soil (mixes). Specifically, these four parts involve the following:

- Determination of the design permeant that appropriately represents a reasonable “worst-case” chemical make-up of groundwater from the LB site

- Develop, test and select slurries (e.g., the percent of reagent[s] in water) for mixing with on-site soil along the alignment of the LB barrier wall that are compatible with the design permeant (Tier I)

- Develop, test and select design mixes (e.g., mixtures of selected slurries and on-site soils) that are compatible with the design permeant and meet the desired hydraulic conductivity ($\leq 1x10^{-7}$ cm/sec) as shown during short-term testing (Tier II)

- Refine and test at least two successful design mixes for long-term compatibility and hydraulic conductivity (Tier III)

Design Permeant Selection

A "worst case" design permeant was selected by evaluation of analytical data from groundwater wells sampled in the area of the LB barrier wall. Previous experience from other slurry/barrier wall projects (Ryan 1987 and Day 1994) have shown that standard bentonite (the most common clay used in low permeability walls) may be more susceptible to negative effects from high inorganic concentrations, comparable to those found near the LB, as compared to the organic concentrations detected in samples from wells in the area. As a result, the reasonable "worst case" groundwater was based on primarily inorganic chemistry (the presence of cations is likely to be the driving factor in compatibility).

Tier I Results

In Tier I four different commercial clay products were tested: bentonite (Fed Jel 90), attapulgite (HY Attapulgite), salt-resistant bentonite (SW 101), and sepiolite. The properties of the clays when mixed with the non-potable water available on site are shown in the Table 1 below.

Table 1. Tier I Test Results

Properties	Typical*	Bentonite	Attapulgite	Salt-Resistant Bentonite	Sepiolite
Clay / Water (ratio in %)	5 to 7	6	6	6	6
Funnel Viscosity (MF sec.)	40	34	38	>120	33
Apparent Viscosity (AV cP)	>15	8.5	28.5	78	17.5
Yield Point (lb / 100 sf)	20	5	41	72	25
YP / PV (ratio)	< 3	0.8	5	1.7	5
Filtrate Loss (ml/30 min.)	<20	17.6	146	7.5	103
Cake Thickness (mm)	0.8 to 2.4	2.0	6.6	1.3	4.8
Residue > 0.075 mm (%)+	<4	<4	<8	<4	<8
As Received Moisture Content (%)+	<10	<10	<16	<10	<16
Slurry Density (pcf)	64 to 65	64	64.5	64	64.5
Slurry pH	7 to 9	8.2	9.5	8.7	8.5

* Typical of bentonite drilling fluid.

\+ Manufacture's or API 13A specification

The properties of each clay slurry are different from each other, and even the bentonite clay is not as viscous as a typical bentonite slurry. The atypical performance of the bentonite clay was attributed to the high mineral content of the non-potable mixing water. The non-potable water has both a high hardness and high alkalinity. The inclusion of an additive, such as soda ash could be expected to alleviate some of the negative effects of the non-potable water on the bentonite.

Each clay was subjected to a series of index tests for compatibility. Modified filter press permeability tests were performed by first completing two standard filtrate tests (30 minutes at 100 psi) with slurry made from the mix water and clay. Next, the supernate from each test was decanted and the two cells (with filter cakes still intact) were refilled with either tap water or groundwater. The test cells were again pressurized (at 100 psi) and the test continued for about 3 hours while the flow rate of the waters through the two filter cakes was monitored. The flow rates can be compared as the ratio of the filtrate of the groundwater (or leachate) to the filtrate of the tap water versus the normalized pore volumes of flow. Graphs of the results are presented in Figure 2. All of the results produced a ratio of less than 2 and thus generally acceptable results.

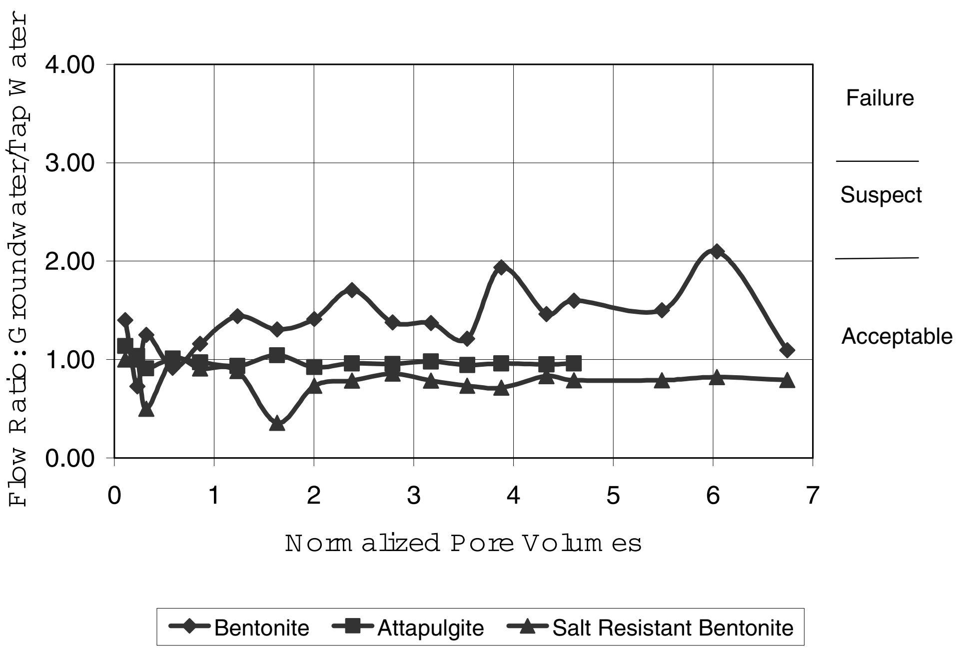

Figure 2. Filter Press Compatibility Test Results

Chemical desiccation tests were performed by mixing standard slurry at a 1:1 ratio with tap water, mix water, and groundwater. These mixtures are poured onto glass plates and allowed to dry. The cracking pattern of the dried slurry is then examined for any unusual patterns. All of the dried slurries appeared nearly identical and there were no indications of unusual cracking patterns and therefore, no obvious incompatibility.

Sedimentation/flocculation tests were also performed to help determine whether the clay will fall out of suspension in the presence of the groundwater. Slurries were made with each of the three different clays (bentonite, attapulgite and salt-resistant bentonite (SRB)) and diluted 1:1 with tap water, mix water, and groundwater, and observed for at least 7 days. The bentonite and attapugite clays diluted with the groundwater produced some unexpected settlement or separation. The separation observed with the groundwater was considered unusual and a potential indication of incompatibility with the groundwater.

Tier IA Results

Due to the potential for an incompatibility with two of the three clays tested (in the sedimentation test), a second set of additives, including blast furnace slag (BFS), and Portland cement (PC), was tested for creating soil-cement mixtures that would rely more on cement instead of commercial clay for their impermeability. Five grouts were tested in Tier IA with properties as shown in Table 2.

Table 2. Tier IA Test Results

Grout No.	Additives	Ratio/W (%)	Density (gm/cc)	AV (cP)	pH (units)	Bleed (%)
1	BFS/Att	12/6	1.11	2.5	9.8	30
2	BFS/Sep	18/4	1.13	2.5	10.0	55
3	BFS/PC/Bento	16.5/5.5/4.0	1.15	4.0	11.8	24
4	BFS/PC/Bento	36/4/2.5	1.24	4.5	11.6	20
5	PC/Bento	19/5.5	1.15	4.0	11.9	28

In addition to tests for viscosity and bleed, the grouts were subjected to two index tests for compatibility with the groundwater; slake and pan set tests. Results of the viscosity and bleed tests are shown in Table 2. While the viscosity of the grouts was low and easily workable, the bleeds were excessive. A grout with excessive bleed could be expected to be more difficult to mix and pump and may separate when mixed with soils. Initially, all of the grout exhibited excessive bleed. Later it was found that adding more clay, altering the order of mixing, and adding soda ash (SA) produced more acceptable bleeds.

In the slake test, hardened cylinders of grout (cured 7 days) are immersed in tap water and groundwater and then compared. Excessive specimen disintegration, flaking or clouding of the water due to immersion is considered unacceptable. After 2 weeks of immersion the test specimens were cut into sections and examined. All of the specimens appeared identical and no obvious incompatibility was observed.

In the pan test, the fluid grout is poured into separate pans filled with either groundwater or tap water. The penetration resistance of the grout is measured as the specimen hardens. An unusual set in the specimen immersed in groundwater compared to the specimen in tap water may indicate an incompatibility. All of the grouts set and there were no obvious effects from the groundwater on the grouts. Based on the Tier IA results we postulated that an acceptable grout could be formulated from a combination of blast furnace slag, Portland cement, bentonite, and soda ash.

Tier II Results

In Tier II four mixtures of SRB mixed with soil and 11 mixtures of cement with soil were formulated and tested. A summary of proportions and properties of the SRB-soil mixtures are shown in Table 3.

Table 3. Soil-Bentonite Tier II Results

TRIAL MIX No.	ADDITIVES	Additives Added (%)	Water Added (%)	Slurry Viscosity (Av in cP)	DSM Slump (inch)	Water Content (%)	Total Density (pcf)	Permeability to Water (cm/sec)
B1	SRB	1.8	45	31	5.75	57.6	97.4	3.60E-06
B2	SRB / SA / Thinner	2 / 0.067 / 0067	33.3	58	3	46.7	106.7	2.70E-07
B3	SRB	3.22	80.5	31	>12	64.5	92.0	7.90E-08
B4	SRB / SA / Thinner	4 / 0.133 / 0.133	66.3	58	12	77.3	92.6	5.80E-09

The SRB-soil mixtures obtained a low, acceptable permeability at addition rates greater than 3%. SRB creates a very thick slurry at low addition rates, so a large volume of water and/or slurry thinners must be added in order to limit the amount of water added. Even for DSM which is essentially a replacement process, a very high water content could complicate construction.

The properties of 11 soil-cement mixtures and two alternate grout mixtures are shown below in Table 4. The permeability of the soil-cement mixtures can be generally divided into distinct groups. The PC–bentonite mixtures (C1 through C3) obtained disappointing and relatively high permeabilites on the order of 1 x 10^{-5} cm/sec. In these mixtures the inclusion of the soil tended to lower the permeability of the mixture. The replacement of up to 75% of the PC with BFS (C4 through C6) produced similar, disappointing permeability results. However, when 89% of the PC was replaced with BFS (mixtures C7 through C9) the permeability of some mixtures dropped by up to 3 orders of magnitude. Higher strengths generally were reflected in lower permeability. The mixtures of BFS and attapulgite clay obtained a low permeability with the grout alone, but higher permeability when mixed with the soil. Based on the trends evident in mixtures C1 through C11 two additional grout mixtures, G12 and G13 were formulated. Mixture G12 with 89% of the PC replaced by BFS and a higher bentonite content produced the best overall permeability. Mixture G13 with SRB instead of bentonite was similar in permeability to mixtures C1 to C3.

Tier III Results

Based on the results from Tier II, new mixtures were made for Tier III. The objective of Tier III was to improve the formulations and test the long term permeability of mixtures that included both the worst case and average case soils. In addition, it was recognized that construction requires a range for productive implementation, so a range in the proportions of additives was investigated.

Five new SRB-soil mixtures were formulated and tested. These mixtures (B10 through B14) are compared with mixtures B3 and B4 (from Tier II) in Table 5. A range in water contents were tested in an attempt to model the likely variety of DSM construction conditions. Mixtures B10 and B11 incorporated the average case soils with the grout. Mixtures B10 and B12 limited the water added to 50% which limited the amount of SRB added to 3.5%. A lignosulfonate thinner was added to all of the mixtures to improve workability and maximize the amount of the SRB added. Mixture B14 was formulated in an attempt to produce a more permeable mixture that would closely simulate the other mixtures (but with a higher permeability) and pass two pore volumes of flow in a lesser time and thus help speed completion of the test program.

Table 4. Soil-Cement Tier II Results

TRIAL MIX No.	ADDITIVE	Additives Added* (%)	Grout Viscosity (AV in cP)	DSM WC (%)	DSM Density (pcf)	DSM UCS 7 day (psi)	DSM UCS 28 day (psi)	Permeability (DSM) (cm/sec)	Permeability (Grout) (cm/sec)
C1	PC I-II / Bentonite	5 / 0.5	2.5	58	99.3	2.4	7.0	3.70E-05	3.40E-05
C2	PC I-II / Bentonite	7 / 0.5	4.5	59.8	100.3	4.3	10	4.40E-05	1.40E-04
C3	PC I-II / Bentonite	9 / 0.5	4.75	60.9	100.6	5.5	13	5.60E-05	1.30E-04
C4	BFS / PC I-II / Bentonite	3 / 1 / 0.5	2	58.8	101	6.4	19	4.70E-05	3.40E-04
C5	BFS / PC I-II / Bentonite	4.5 / 1.5 / 0.5	4	68.9	96.8	14.3	38	4.50E-05	2.20E-04
C6	BFS / PC I-II / Bentonite	6 / 2 / 0.5	4	69.7	96.7	19.9	55	6.00E-06	2.00E-04
C7	BFS / PC I-II / Bentonite	4 / 0.5 / 0.5	2.5	55.5	100.6	10.8	33	3.50E-05	8.40E-06
C8	BFS / PC I-II / Bentonite	8 / 1 / 0.5	2.5	73.7	95.6	28.2	78	5.70E-05	4.40E-07
C9	BFS / PC I-II / Bentonite	12 / 1.5 / 0.5	3	64.1	98.8	70.8	176	5.10E-08	2.60E-07
C10	BFS / Attapulgite / SA	6 / 3 / 0.12	2.5	62.6	98.2	24.6	55	4.90E-07	9.90E-08
C11	BFS / Attapulgite	4 / 2	2	57.4	100.4	14.7	38	2.30E-06	4.70E-07
G12	BFS / PC I-II / Bento/SA	8 / 1 / 3 / 0.12	52	NA	NA	NA	NA	NA	9.10E-08
G13	PC I-II / SRB / SA	9 / 1 / 0.12	6	NA	NA	NA	NA	NA	1.10E-04

*Water added in all cases was 60 percent.

Table 5. Soil-Bentonite Tier III Results

TRIAL MIX No.	SOIL TYPE	ADDITIVES	Additive Added (%)	Water Added (%)	Permeability to Water (cm/sec)	Permeability to Grd Water (cm/sec)	Permeability to Grd Water (cm/sec)	PV Flow
	Soil-Bentonite Mixture				Flow Pump	Initial	Final	
B3	Worst	SW101	3.22	80.5	7.90E-08	---------	---------	-----
B4	Worst	SW101 / SA / ThinzIt	4 / 0.133 / 0.133	66	5.80E-09	---------	---------	-----
B10	Average	SW101 / Ligno	3.5 / 0.34	50	1.60E-08	5.4E-08	3.50E-08	>0.5
B11	Average	SW101 / Ligno	4 / 0.2	80	1.60E-08	4.9E-08	5.50E-08	>0.75
B12	Worst	SW101 / Ligno	3.5 / 0.34	50	3.50E-08	2.4E-07	3.80E-07	>3.0
B13	Worst	SW101 / Ligno	4 / 0.2	80	1.30E-08	1.3E-08	2.00E-08	>0.75
B14	Worst	SW101 / Ligno	2 / 0.2	80	2.00E-08	6.1E-08	1.00E-07	2.0

Several procedural issues should be noted. All permeability tests to water (Tier II and Tier III) used the flow pump method (ASTM D5084) while the long term tests used the constant head method (ASTM D5084 and D7100). Even though the same sample was tested, the result of using different tests was often different results. In addition, ASTM standard D7100 requires the monitoring of the influent and effluent chemistry of the permeant. For Tier III, the pH and electrical resistivity (a.k.a.

inverse of conductivity) of the permeant were tested at 0.25 pore volume intervals. The results from 70 days of testing mixture B14 is shown in Figure 3.

For mixture B14, the long term permeability tends to oscillate about 1 x 10^{-7} cm/sec. and the result is considered to conclusively demonstrate long term compatibility. The resistivity of the permeant gradually converged to about 1 at two pore volumes, but the pH of the influent and effluent did not produce a similar useful convergence on other tests.

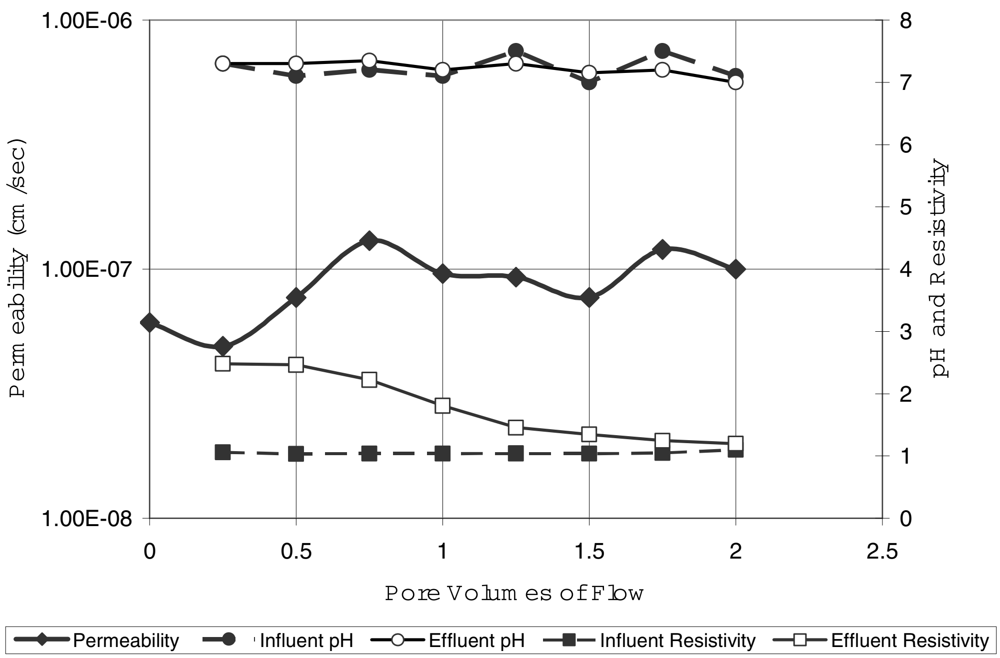

Figure 3. Long Term Data for Mix B14

Five new soil-cement mixtures were also formulated and tested. These mixtures (C15a through C15e) are compared with mixture C9 (from Tier II) in Table 6. Mixtures C15a through C15d were formulated similarly to B10 through B13 to model variable water contents in DSM construction. Mixtures C15a and C15b incorporated the average case soils with the grouts. Both soda ash (SA) and lignosulfonate (Ligno) thinner were included in the formulations. A range of water added, from 40 to 80%, was tested. Mixture C15e was formulated in an attempt to produce a more permeable mixture that would closely simulate the other mixtures (but with a higher permeability) and pass two pore volumes of flow in less time and thus help speed completion of the test program.

The result of testing soil-cement mixture C15e, after 112 days, is shown in Figure 4. For mixture C15e, the long term permeability tends to rapidly decrease to near zero and "plug" the test specimen. Repeated efforts to clean the test apparatus lead to the conclusion that the sample itself, not the test apparatus was plugging. It should be noted that "plugging" is a positive development for permeability performance, though it complicates the demonstration of long term compatibility. In fact, plugging is the ideal result for a groundwater barrier. Once again only the resistivity data produced a converging trend and the pH of the influent and effluent never converged in any soil-cement permeability test.

Most of the long term tests on the soil-cement mixtures produced a steadily decreasing permeability as the test specimen continued to cure. It is possible that the test itself, by increasing the confining stress on the specimen accelerated or exasperated this trend.

Table 6. Soil-Cement Tier III Results

TRIAL MIX No.	SOIL TYPE	ADDITIVES	Additive Added (%)	Water Added (%)	Permeability to Water (cm/sec)	to Grd Water (cm/sec)	to Grd Water (cm/sec)	PV Flow
		Soil-Cement Mixtures			Flow Pump	Initial	Final	
C9	Worst	BFS / PC / Bento	12 / 1.5 / 0.5	60	5.1E-08	---------	---------	---------
C15a	Average	BFS / PC / Bento / SA / Ligno	10 / 1 / 3 / 0.12 / 0.1	40	1.5E-07	9.7E-08	1.70E-08	<0.25
C15b	Average	BFS / PC I-II / Bentonite / SA	10 / 1 / 3 / 0.12	80	2.2E-07	3.2E-07	1.70E-07	< 1.5
C15c	Worst	BFS / PC / Bento / SA / Ligno	10 / 1 / 3 / 0.12 / 0.1	40	5.9E-08	1.1E-07	5.10E-08	>0.25
C15d	Worst	BFS / PC I-II / Bentonite / SA	10 / 1 / 3 / 0.12	80	4.6E-08	1.1E-07	1.90E-09	<0.5
C15e	Worst	BFS / PC I-II / Bentonite / SA	8 / 1 / 3 / 0.12	80	3.3E-07	3.7E-07	4.00E-09	<1

CONCLUSION

Based on the results, either the SRB-soil or soil-cement mixtures can be acceptable for implementation. The SRB-soil mixtures with a minimum of 4% SRB added is compatible with the groundwater and should produce an acceptable permeability. Current expected material cost for the SRB-soil barrier is about $20/cy. The challenge with the SRB-soil mixtures will be dealing with the excess water and muddy spoils. The judicious use of thinners is expected to minimize cleanup time and costs. It is also expected that the final surface of the completed DSM wall will be treated with PC to create a stable surface.

The soil-cement mixture is also technically equal to the SRB-soil mixtures. However, the number, complication, and cost of additives is a disadvantage. The currently estimated material cost of the soil-cement barrier is about $35/cy. Since the mixture sets, clean up costs should be reduced and simplified. Based on past experience, it is often more difficult to demonstrate that field samples of the soil-cement meet specification, due to the delay incurred while the samples cure and obtain their final permeability.

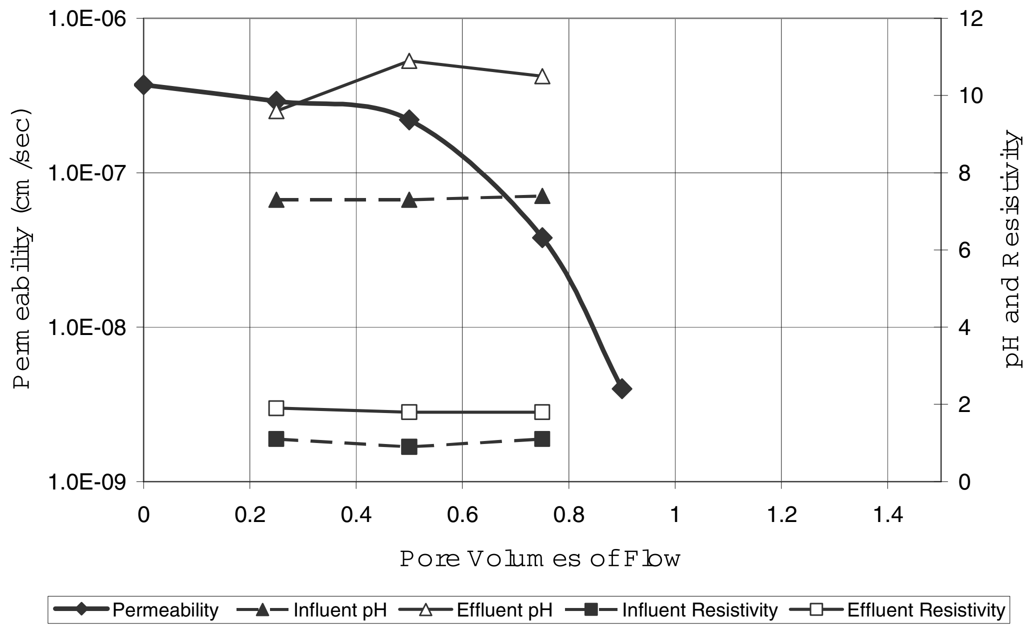

Figure 4. Long Term Data for Mix C15E

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