

# Evaluation of Different Slurry Materials for Containment Wall Construction at a Dense Nonaqueous Phase Liquid-Contaminated Site

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**Abstract:** A water-bearing granular soil layer within the subsurface of a former manufactured gas plant (MGP) site is impacted with tarry dense nonaqueous phase liquid (DNAPL). A containment wall constructed with the vibrated beam method is considered feasible. Different slurry materials were tested and then selected to prevent the migration of DNAPL to offsite properties. This paper presents the slurry compatibility study to evaluate different self-hardening slurry materials for their compatibility with the DNAPL. Specifically, the study simulated the emplacement of slurry material in the granular unit that is impacted with DNAPL and determined the effect of DNAPL interaction with the slurry material on permeability and shear strength of hardened slurry. Four different types of slurry materials, namely cement-sodium bentonite-dispersant, cement-sodium bentonite, cement-calcium bentonite, and IMPERMIX (slag cement and Attapulgitic clay mix) were used to prepare cylindrical samples under different simulated emplacement conditions (mixing or pouring with site DNAPL) and were cured. Both permeability and unconfined compression tests were conducted on the cured slurry samples. Both groundwater and DNAPL were used as permeants in permeability testing. Overall, the results showed that the IMPERMIX slurry possesses low permeability (less than  $10^{-8}$  cm/s) and high shear strength for all of the simulated test conditions. Because of good chemical compatibility and ease to use with the vibrated beam construction method, IMPERMIX slurry mix was recommended for the construction of the containment wall at the site.

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## Introduction

A water-bearing granular soil layer within the subsurface of a former manufactured gas plant (MGP) site is impacted with tarry dense nonaqueous phase liquid (DNAPL). The DNAPL is coal tar (CT), which is a by-product of former manufactured gas operations. Tarry material is one of the bulk residuals of the manufactured gas process that converted coal, coke, and oils into gas (Hayes et al. 1996). The site occupies approximately four acres of land and is surrounded by a mixture of residential and industrial properties.

In order to contain the DNAPL at the site, a slurry containment wall was constructed. The soils at the site could not be used for the construction of a conventional soil-bentonite wall due to the

presence of DNAPL-contaminated soils along the proposed alignment of the wall. If any of the contaminated soils are excavated, these soils will require proper disposal or treatment to the required cleanup objectives. Consequently, cement-bentonite slurries or similar slurries that do not require soil were considered suitable materials for the construction of the containment wall using the vibrated beam method. As shown in Fig. 1, the vibrated beam method essentially consists of vibrating a customized, built-up steel 33-in. wide flange beam from the surface to the impervious layer while a premixed slurry is injected through the nozzles affixed to the bottom of the beam. After the slurry beam attains the required depth, the beam is extracted at a controlled rate to fill the void left by the beam extraction, creating an in-ground panel of slurry. This process is repeated along the line of the wall, with each beam insertion overlapping the previously inserted panel, creating a continuous barrier wall. This construction method minimizes the disposal/management of excavated contaminated soils and any potential undesirable air emissions as well as minimizes the construction time and cost.

Published studies on the compatibility of slurry materials with DNAPL are very limited. Site contamination varies from site to site and a site-specific investigation based on the actual DNAPL found at the site is critical for the selection of suitable slurry materials. Laboratory testing was conducted to determine the compatibility of different self-hardening slurry materials with the DNAPL found at the site. Specifically, four different commonly used slurry materials were selected for this investigation: cement-sodium bentonite-dispersant, cement-sodium bentonite, cement-calcium bentonite, and IMPERMIX (slag cement and Attapulgitic clay mix). The laboratory testing simulated the emplacement of slurry material in the granular unit that is impacted with DNAPL

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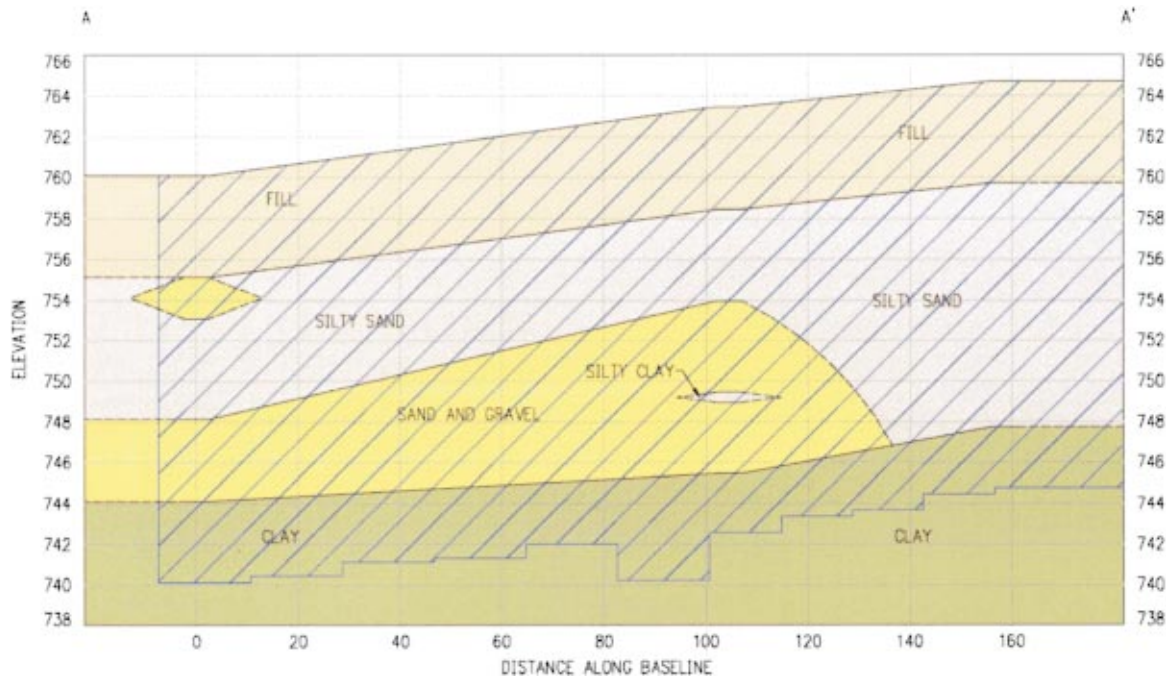


Fig. 2. (Color) Cross section of site soils with overlay of containment wall

cific objective was to simulate the emplacement of slurry material in the granular unit that is impacted with DNAPL and to determine the effect of DNAPL interaction with the slurry material on permeability and shear strength of hardened slurry.

## Experimental Methodology

### Materials

DNAPL was recovered from on-site granular soil with an interceptor trench and stored in a tank. The DNAPL is a viscous multicomponent hydrocarbon. The major constituents of the DNAPL are polycyclic aromatic hydrocarbons (PAHs) and the minor constituents are volatile organic compounds (VOC) primarily benzene, toluene, ethylbenzene, and xylenes (BTEX). The viscosity of the DNAPL ranges from 60 to 150 centipoise (cP) at 24°C (75°F) and its density is approximately 1.08 g per cubic cm (g/cm<sup>3</sup>). For single-phase flow, the relative mobility of the water to DNAPL is the ratio of density/viscosity ( $\rho/\mu$ ) for water to  $\rho/\mu$  for DNAPL (Fetter 1999). Thus water is 62–155 times more mobile than the DNAPL, based on the range of DNAPL viscosity.

Groundwater was obtained from the monitoring wells installed within the granular soil layer at the site. The concentrations of selected metals, BTEX and PAHs contained in the site groundwater are presented in Table 1. The groundwater pH ranges from pH 6.8 to 7.2.

Four different slurry compositions were prepared and tested: cement-sodium bentonite-dispersant (C-SB), cement-sodium bentonite (C20-SB6), cement-calcium bentonite (C-CB), and IMPERMIX (I) that consists of slag cement and Attapulgite clay mix. The slurry compositions are presented in Table 2. All solid proportions are by weight of water. Portland Type I cement was used. Wyoming sodium bentonite and SS-1 dispersant were provided by Slurry Systems, Inc., Gary, Ind. Calcium bentonite (CAL-BEN) was obtained from CIMBAR Performance Minerals, Catersville, Ga. The IMPERMIX slurry generally consists of

water and in a proportion by weight of water of about 5–8% of Attapulgite clay and about 7.5–15% of slag cement [G. R. Tallard, “Self-hardening slurry mix,” U.S. Patent No. 4,726,713 (1988)]. The specific composition of IMPERMIX selected for this study was provided by Liquid Earth Support, Inc., Pelham, N.Y.

### Slurry Sample Preparation

Table 2 also summarizes all of the slurry samples (including their compositions and designations) prepared for this study. For the preparation of cement-bentonite slurry samples (C-SB, C20-SB6, and C-CB), the required amounts of tap water and groundwater were agitated with a mixer and then bentonite was added to the water. When the bentonite was completely hydrated, Portland Type I cement was added and mixing was continued until a stable suspension was obtained. For the preparation of IMPERMIX slurry samples, the solids were added to the agitated water as received, and mixed until a stable suspension was obtained. Each slurry mix was poured into two cylindrical stainless steel molds and two Plexiglas molds. The inside diameter and length of each mold was 3.5 and 12 in., respectively. The Plexiglas molds were used in order to observe physical changes that occur during the

Table 1. Concentration of Groundwater Constituents

Constituent	Concentration (mg/L)
Ca	201
Mg	23
Na	10
Total RCRA metals (As, Ba, Cd, Cr, Pb, Hg, Se, Ag)	<0.05
Total BTEX	<1.0
Total PAHs	<1.0

Note: RCRA=Resource Conservation Recovery Act; BTEX=benzene, toluene, ethylbenzene, and xylene; and PAH=polycyclic aromatic hydrocarbons.

**Table 2.** Slurry Materials Selected and Samples Prepared for this Study

Slurry type/designation	Slurry composition	Samples prepared	Sample designation
Cement-sodium bentonite-dispersant (C-SB)	5.4% sodium-bentonite	C-SB	C-SB
	10.2% Portland Type I cement	C-SB with 20% DNAPL mixed	C-SB-20-M
	0.4% SS-1 dispersant <sup>a</sup>	C-SB with 20% DNAPL poured	C-SB-20-P
	67.2% tap water	C-SB with 10% DNAPL mixed	C-SB-10-M
	16.8% site groundwater	C-SB with 10% DNAPL poured	C-SB-10-P
Cement-sodium bentonite (C20-SB6)	6% sodium-bentonite (SB)	C20-SB6	C20-SB6
	20% Portland Type I cement	C20-SB6 with 20% DNAPL mixed	C20-SB6-20-M
	59.2% tap water	C20-SB6 with 20% DNAPL poured	C20-SB6-20-P
	14.8% site groundwater	C20-SB6 with 10% DNAPL mixed	C20-SB6-10-M
		C20-SB6 with 10% DNAPL poured	C20-SB6-10-P
Cement-calcium bentonite (C-CB)	12% calcium-bentonite	C-CB	C-CB
	15% Portland Type I cement	C-CB with 20% DNAPL mixed	C-CB-20-M
	58.4% tap water	C-CB with 10% DNAPL mixed	C-CB-10-M
	14.6% site groundwater		
IMPERMIX (I)	5% Attapulgite clay	IMPERMIX (I)	I
	10% slag cement	I with 20% DNAPL mixed	I-20-M
	68% tap water	I with 20% DNAPL poured	I-20-P
	17% site groundwater	I with 10% DNAPL mixed	I-10-M
		I with 10% DNAPL poured	I-10-P

<sup>a</sup>Provided by Slurry Systems, Inc.

sample preparation and curing, while the stainless steel molds were used to ensure compatibility with the DNAPL and groundwater.

Two additional sets of samples were prepared with cement-bentonite slurry (C-SB, C20-SB6, and C-CB) and IMPERMIX slurry to simulate their potential interaction with DNAPL during the construction of the containment wall. One set of samples was prepared by pouring DNAPL onto the slurry to simulate the contact of DNAPL with the slurry material during emplacement (poured condition). Another set of samples was prepared by mixing DNAPL with the slurry in the mixer to simulate potential mixing of DNAPL with the slurry material during emplacement (mixed condition). The mixed and poured conditions were prepared with two DNAPL proportions, 10 and 20% by total volume of liquids (tap water, site groundwater, and DNAPL) to simulate varying degrees of DNAPL contact during emplacement (both mixed and poured conditions). The sample designations for these samples are shown in Table 2.

All samples were prepared under an environmental hood at room temperature. Immediately after the preparation, all molds were covered with a plastic cap and kept in an environmental chamber for curing under constant temperature ( $23 \pm 2^\circ\text{C}$ ) and constant humidity ( $\approx 95\%$ ) conditions. During the curing process the physical changes that the samples in the Plexiglas molds underwent were recorded with photographs. After 28 days of curing, the molds were removed from the environmental chamber. The hardened samples were carefully extruded from the molds, while the soft samples were left within the molds.

### Slurry Sample Testing

Water content ( $w$ ) and wet and dry densities ( $\rho_t$  and  $\rho_d$ ) of all extruded samples were determined. The moisture content was determined in accordance with the standard testing procedure ASTM D4959. For the wet density determination, the dimensions and mass of the extruded cylindrical slurry samples were mea-

sured, and the wet density was calculated by dividing the mass by the volume. The dry density was calculated using  $\rho_d = \rho_t / (1 + w)$ . The samples extruded from the stainless steel molds were used to conduct triaxial permeability tests and unconfined compression tests. The permeability tests were conducted using the test apparatus shown in Fig. 3. The permeability of DNAPL and groundwater were tested in the triaxial cell under different hydraulic gradients. During the testing, the inflow pressure was varied to create different hydraulic gradients. A small difference in pressure between the inflow pressure and confining pressure (cell pressure), generally less than 2 psi, was maintained during the course of the testing. Under each constant hydraulic gradient condition, the quantity of DNAPL or groundwater that flowed through the sample was measured at different time periods. The permeability was then calculated using Darcy's equation:  $Q = KiA$ ; where  $K$  = permeability ( $L/T$ ),  $Q$  = flow rate through the sample ( $L^3/T$ ),  $i$  = constant hydraulic gradient ( $L/L$ ), and  $A$  = cross-sectional area of the sample ( $L^2$ ).

The hardened slurry samples were also tested for unconfined compressive strength according to the procedure set forth in ASTM D 2166. Prior to this testing, the slurry samples were immersed in groundwater or DNAPL for two weeks. The samples were then loaded under controlled strain until they failed. During the loading, displacement and normal load were measured. The failure load was used to calculate unconfined compressive strength ( $q_u$ ). The undrained shear strength ( $S_u$ ) is then calculated using  $S_u = q_u/2$ . Samples which were soft even after curing for 28 days were not tested for unconfined compressive strength; however, they were tested within the molds for undrained shear strength based on a handheld vane shear apparatus (ASTM D4648). This testing essentially involved pushing the vane into the sample and rotating until it completely sheared the slurry sample. The maximum torque required for complete shearing of the sample was then used to calculate the undrained shear strength of the sample.

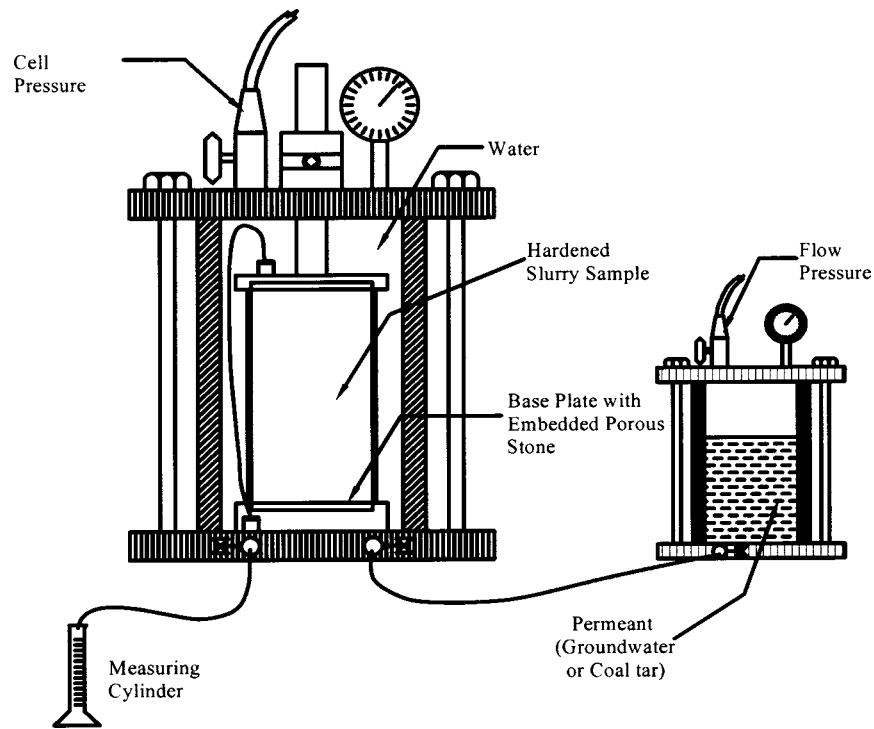


Fig. 3. Schematic of triaxial permeability test apparatus used for this study

## Results and Discussion

### Physical Changes during Curing

All slurry molds were observed for changes in consistency and color during the course of curing. Plexiglas molds allowed periodic photographing of the slurry samples to observe physical changes that the slurry samples underwent during the curing process. The slurry samples prepared with low cement content, sodium bentonite and dispersant (C-SB) were white in color. The color did not change and the samples remained very soft at the end of the curing period of 28 days. The DNAPL that was poured on the freshly prepared slurry samples (C-SB-10-P and C-SB-20-P) remained on the top of the slurry. When DNAPL was mixed with the slurry (C-SB-10-M and C-SB-20-M), the color of the slurry was brown. Both DNAPL poured- and mixed-slurry samples remained soft at the end of the curing period.

The slurry prepared with high cement content and sodium bentonite and without dispersing agent (C20-SB6) possessed white color. However, the slurry had a consistency of thick paste. As a result, the slurry was placed in the mold and tamped with a pestle. The DNAPL placed on the top of the freshly prepared samples (C20-SB6-10-P and C20-SB6-20-P) remained on the top of the sample. Samples turned a green color and hardened after a curing period of 28 days. The samples mixed with DNAPL (C20-SB6-10-M and C20-SB6-20-M) had a brown color and hardened after curing for 28 days.

The slurry samples made with cement and calcium bentonite (C-CB) gradually turned into a green color during hardening. C-CB samples with poured and mixed DNAPL exhibited similar characteristics as those of high cement content and sodium bentonite slurry samples (C20-SB6). The thick consistency of the C20-SB6 and C-CB slurry samples implies that these slurry mixes may not be suitable to use with the vibrated beam method.

All of the IMPERMIX slurry samples were initially white in color and they gradually changed to green color upon curing. When DNAPL was poured on the freshly prepared IMPERMIX samples, the DNAPL remained on the top of the sample. Migration of DNAPL along the edges of the mold walls was observed in some samples. Sectioning of the cured samples revealed that the DNAPL did not penetrate into the IMPERMIX samples. The IMPERMIX samples mixed with DNAPL were brown in color and retained the same color even after curing. All of the IMPERMIX samples were hard at the end of curing.

### Permeability

As mentioned before, C-SB samples did not sufficiently harden and were therefore not suitable for permeability testing. The samples could not be permeated with DNAPL. The permeability test results for other slurry materials tested are summarized in Table 3. The range and mean permeability of the samples for the entire range of hydraulic gradients is presented in this table. The high cement and sodium bentonite (C20-SB6) slurry samples showed permeability ranging from  $1 \times 10^{-5}$  to  $3 \times 10^{-8}$  cm/s. The permeability to water was approximately  $1 \times 10^{-7}$  cm/s, while the permeability to DNAPL (coal tar) was approximately  $3 \times 10^{-8}$  cm/s. The low permeability to DNAPL may be due to the high viscosity of DNAPL, which caused low mobility through the sample. The samples prepared with DNAPL poured condition exhibited permeability to groundwater from  $1 \times 10^{-7}$  to  $3 \times 10^{-8}$  cm/s. These values fall within the range found for C20-SB6 without DNAPL. DNAPL penetration under the 10% DNAPL poured condition may be insignificant and the permeability of this slurry was close to the permeability of the slurry that did not interface with DNAPL. However, for the 20% DNAPL poured condition, it is possible that some DNAPL diffused or permeated into the slurry sample, causing some DNAPL entrap-

**Table 3.** Permeability of Cement-Sodium Bentonite, Cement-Calcium Bentonite, and IMPERMIX Slurry Samples

Sample designation	Permeant	Gradient	Permeability, $K$ (cm/s)	Average $K$ (cm/s)
Cement-sodium bentonite slurry samples				
C20-SB6-GW	Groundwater	28	1.63E-7	1.24E-7
		55	1.53E-7	
		83	1.05E-7	
		111	7.87E-8	
C20-SB6-CT	Coal tar (DNAPL)	27	3.84E-8	3.72E-8
		55	3.50E-8	
		83	3.82E-8	
C20-SB6-20M-GW	Groundwater	29	5.43E-6	1.38E-5
		58	1.01E-5	
		87	1.31E-5	
		116	2.66E-5	
C20-SB6-20P-GW	Groundwater	27	0	2.74E-8
		55	7.34E-8	
		82	1.28E-8	
		110	2.35E-8	
C20-SB6-10M-GW	Groundwater	27	1.31E-8	2.25E-7
		55	3.95E-7	
		82	4.82E-7	
		110	1.02E-8	
C20-SB6-10P-GW	Groundwater	29	1.18E-7	1.15E-7
		57	2.31E-7	
		86	4.25E-8	
		114	6.78E-8	
Cement-calcium bentonite slurry samples				
C-CB-GW	Groundwater	33	0	4.30E-10
		46	0	
		66	0	
		93	1.72E-9	
C-CB-CT	Coal tar (DNAPL)	37	0	0
		51	0	
		73	0	
		95	0	
C-CB-20-M-GW	Groundwater	31	0	0
		44	0	
		63	0	
		94	0	
C-CB-10-M-GW	Groundwater	44	0	5.54E-9
		61	2.66E-9	
		87	1.60E-9	
		105	1.79E-8	
IMPERMIX slurry samples				
I-GW	Groundwater	49	1.48E-8	7.54E-9
		68	1.68E-9	
		98	7.13E-9	
		122	6.59E-9	
I-CT	Coal tar (DNAPL)	33	0	0
		46	0	
		59	0	
I-20-M-GW	Groundwater	42	0	1.62801E-8
		59	2.35E-8	
		76	2.28E-8	
		122	1.88E-8	
I-20-P-GW	Groundwater	47	0	0
		66	0	
		94	0	
		122	0	
I-10-M-GW	Groundwater	48	0.00E+00	9.35E-9
		67	1.56E-8	
		86	1.19E-8	
		122	9.91E-9	
I-10-P-GW	Groundwater	41	0	0
		58	0	
		83	0	
		122	0	

Note: Low cement and sodium bentonite slurry samples were very soft and were not tested.

**Table 4.** Unconfined Compressive Strength and Related Parameters for Slurry Samples

Sample designation	Moisture content (%)	Dry density (g/cm <sup>3</sup> )	Unconfined compressive strength, $Q_u$ (psf)	Strain at failure (%)	Undrained shear strength, $S_u$ (psf)
C20-SB6-GW	236.1	0.42	45,779	1.9	22,889
C20-SB6-CT	238.2	0.42	13,652	4.9	6,826
C20-SB6-20M-GW	175.3	0.52	8,001	3.7	4,000
C20-SB6-20P-GW	192.9	0.44	15,132	5.0	7,566
C20-SB6-10M-GW	146.5	0.47	26,361	2.1	13,180
C20-SB6-10-P-GW	178.6	0.43	43,995	2.1	21,997
C-CB-GW	236.1	0.33	9,827	4.4	4,913
C-CB-CT	238.2	0.34	11,209	5.2	5,604
C-CB-20-M-GW	175.3	0.43	6,904	4.0	3,452
C-CB-10-M-GW	192.9	0.41	7,705	3.3	3,852
I-GW	312.8	0.21	8,448	8.0	4,224
I-CT	453.2	0.19	8,491	5.7	4,245
I-20-M-GW	321.1	0.2	5,502	2.5	2,751
I-20-P-GW	470.6	0.2	5,841	4.6	2,920
I-10-M-GW	364.7	0.23	5,837	2.4	2,918
I-10-P-GW	444.4	0.21	7,901	3.9	3,950

ment which may have caused permeability to groundwater to be the same as to DNAPL. For the C20-SB6 samples with 10% DNAPL mixed condition, the permeability to groundwater was  $2 \times 10^{-7}$  cm/s, which is slightly higher than the sample that was not mixed with DNAPL. For the sample with 20% DNAPL, the permeability to groundwater increased to  $1 \times 10^{-5}$  cm/s, approximately two orders of magnitude. These results imply that the mixing of the slurry with a greater amount of DNAPL has the potential to increase the permeability substantially.

In general, the cement-calcium bentonite (C-CB) slurry samples were less permeable than cement-sodium bentonite (C20-SB6) slurry samples. The permeability of C-CB slurry to groundwater was found to be  $4 \times 10^{-10}$  cm/s. The permeability value was too low to measure when DNAPL was used as permeant. DNAPL-mixed C-CB samples also exhibited very low permeability values. For 10% DNAPL mixed conditions, the permeability to groundwater was found to be  $5 \times 10^{-9}$  cm/s which is an order of magnitude lower than the value found for the baseline condition that did not undergo any DNAPL mixing. However, for 20% DNAPL mixed condition, the permeability to groundwater was too low to measure. Overall, it appears that C-CB slurry possessed a low permeability to groundwater as well as to DNAPL and it appears that this slurry mix is less influenced by the interaction with the DNAPL.

The permeability of IMPERMIX samples was less than  $1 \times 10^{-8}$  cm/s for all the poured conditions tested in this study. The permeability to groundwater was  $7 \times 10^{-9}$  cm/s and to DNAPL was too low to measure. For the 10 and 20% DNAPL poured conditions, the permeability to groundwater was also too low to measure. For both 10 and 20% DNAPL mixed conditions, the permeability to groundwater was approximately  $1 \times 10^{-8}$  cm/s. This result shows that the amount of DNAPL present in the slurry does not significantly affect the permeability to groundwater. Overall, IMPERMIX slurry showed lower permeability characteristics under various simulated conditions.

As seen from Table 3, the permeability values were not significantly affected by the applied gradients that ranged approximately from 27 to 122. The results reveal that the permeability of the slurry samples that did not contain DNAPL increased in the order C-CB < IMPERMIX < C20-SB6. The permeability of C-CB and IMPERMIX samples that contained DNAPL was comparable

or less than that of C20-SB6 samples that contained DNAPL. The IMPERMIX samples were impermeable for DNAPL, probably due to the inability of the viscous DNAPL to overcome the capillary forces of IMPERMIX pores. In contrast to the samples with mixed DNAPL, the samples with poured DNAPL were impermeable for groundwater, presumably due to the clogging of the pores by DNAPL. The DNAPL poured onto the C-CB slurry formed a separate liquid phase and did neither permeate nor penetrate the slurry. Consequently, C-CB with poured DNAPL was impermeable to DNAPL. C-CB with the higher proportion of DNAPL was also impermeable to groundwater.

### Shear Strength

The C-SB samples did not sufficiently harden even after 28 days of curing and were therefore not suitable for unconfined compression testing. The shear strength of these samples was determined by handheld vane shear testing. Based on this testing, the undrained shear strength was found to range from 0 to 0.5 psf. As mentioned earlier, all the other slurry samples hardened after curing for 28 days. These samples were extruded, and the moisture content and the dry density of each sample were determined (Table 4). The moisture content and dry density of C20-SB6 samples ranged from 146 to 238% and 0.42 to 0.52 g/cm<sup>3</sup>, respectively. The moisture content and dry density of C-CB samples ranged from 175 to 238% and 0.33 to 0.43 g/cm<sup>3</sup>. On the other hand, the IMPERMIX samples had moisture contents ranging from 312 to 470% and dry densities ranging from 0.19 to 0.23 g/cm<sup>3</sup>.

As mentioned earlier, the hardened samples were immersed in groundwater or DNAPL for two weeks and subsequently tested for unconfined compression strength. The unconfined compressive strengths and related parameters for the samples are presented in Table 4. The stress-strain data obtained from the unconfined compression tests indicate that all different hardened slurry materials exhibited brittle characteristics with failure strain ranging from 1.9% to 8.0%.

For C20-SB6 samples, the undrained shear strength was found to be 22,889 and 6,826 psf for groundwater and DNAPL exposure conditions, respectively. The presence of DNAPL in slurry has resulted in a significant decrease in the undrained shear strength

by as much as 70%. For the 10 and 20% DNAPL poured conditions, the undrained shear strength of the slurry was 21,997 and 7,566 psf, respectively. This result indicates that DNAPL penetration into the slurry was higher under 20% DNAPL poured condition, thus reducing the undrained shear strength by about 65%. For 10 and 20% DNAPL mixed conditions, the undrained shear strength of slurry was 13,180 and 4,000 psf, respectively. Again, these results show that with 20% DNAPL mixed condition, the amount of DNAPL present in the slurry sample was higher and hence reduced undrained shear strength by about 82%. Overall, the results indicate that the reduction in undrained shear strength is proportional to the amount of DNAPL present in the sample.

For the C-CB samples, the undrained shear strength was 4,913 and 5,604 psf for groundwater and DNAPL exposure conditions, respectively. It is rather surprising that the undrained shear strength of the C-CB sample exposed to DNAPL was higher than that exposed to groundwater. For 10 and 20% DNAPL mixed conditions, the undrained shear strength was 3,852 and 3,452 psf, respectively. These results show that the mixing with DNAPL reduces the undrained shear strength of slurry samples by 21–29%.

IMPERMIX slurry samples exposed to groundwater and DNAPL possessed undrained shear strength of 4,224 and 4,245 psf, respectively. These results show that DNAPL had a minimal influence on the undrained shear strength of IMPERMIX samples. For 10 and 20% DNAPL poured conditions, the undrained shear strength of IMPERMIX was 3,950 and 2,920 psf, respectively; these values correspond to 6 and 30% reduction as compared to the strength of the slurry that did not contain DNAPL and was exposed to groundwater. For 10 and 20% DNAPL mixed conditions, the undrained shear strength was 2,918 and 2,751 psf, respectively. These values correspond to a decrease of 30–35% in undrained shear strength as compared to the strength of the slurry that was not exposed to any DNAPL mixing condition.

Overall, the unconfined compressive strength or undrained shear strength of slurry samples that did not contain DNAPL increased in the order IMPERMIX < C-CB < C20-SB6. In general, the unconfined compressive strength of the samples that contained DNAPL was less than that of the samples without DNAPL. The unconfined compressive strength of samples that contained DNAPL also increased in the same order IMPERMIX < C-CB < C20-SB6. In general, the unconfined compressive strength (undrained shear strength) decreases with increasing DNAPL content.

## Conclusions

A comparison of cured slurry samples that did not contain DNAPL revealed that less slag cement than Portland cement was

required in the slurry mix to reduce the permeability. The undrained shear strength of slurry samples containing DNAPL increased with the increase of cement content. Conversely, the permeability of samples containing DNAPL decreased with the decrease of cement content. The solids content of the slurry samples tested increases in the order IMPERMIX (15%), C-SB (16%), C20-SB6 (26%), and C-CB (27%). The overall surface area of solids for the sorption of DNAPL increased with the increase of solids content. It seemed that slurries with high solids content that contained DNAPL had more surfaces available for hydration and chemical bonding than the slurries with low solids content. The chemical bonding ultimately develops the cohesion of the cured material. For the samples that contain DNAPL, the texture of the cured samples with higher solids content had greater permeability than the cured samples with lower solids content. The pore space of cured samples with lower solids content seemed to be occupied by DNAPL. The DNAPL within the pore space may have repelled water and prevented flow through the sample.

While all of the tested slurry mixes seemed compatible with DNAPL (coal tar), the construction of a containment wall with the slag cement and Attapulgitic clay slurry requires much less effort than the construction with C-CB and C-SB material, due to their paste-like consistency. IMPERMIX can be readily pumped and injected, whereas the other mixes are not pumpable. Therefore IMPERMIX was used for the containment wall construction to effectively prevent migration of DNAPL to offsite properties.

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