TEST REPORT #10
Bench-Scale Hydraulic Conductivity as a Function of Product Formulation and Permeant Salinity

Background and Purpose of Testing

In situ capping is a viable alternative for managing contaminated sediments in various aquatic environments, including fresh, brackish, and saline waters. Creation of a relatively low-permeable barrier is often an important management goal when capping sediments in all such environments.

As illustrated in Test Report No. 9, different formulations of the AquaBlok® barrier technology – including those containing sodium bentonite (reactive clay, sodium montmorillonite), attapulgite (a.k.a. palygorskite), or clay blends (sodium bentonite plus attapulgite) - tend to hydrate and expand to varying degrees when exposed to waters of different salinity levels. In addition to differences in *physical* responses, the different product formulations can also display varied *hydraulic* responses as a result of recognized differences in the permeability (hydraulic conductivity) of bentonite and attapulgite based materials to saline waters (e.g. Stern and Shackelford, 1998; Tobin and Wild, 1986; Day, 1994). An understanding of the salinity environment into which the capping material is being placed is critical to determining the most appropriate formulation, and coverage rate, required to achieve a target thickness and permeability for a proposed cap.

The permeability of some clay based environmental barriers can also depend on the *stage* or *sequence* at which saline waters are permeated. For example, the hydraulic conductivity of sodium bentonite-based materials to saline waters can be significantly lower, at least in the short term, if the material is first hydrated and permeated with freshwater (Lin and Benson, 2000; Shackelford, 1994). This and other factors should be considered when determining the most appropriate product formulation for site use – and even the best timing for product placement – in that many impacted coastal (estuarine) environments display significant spatial and temporal variability in salinity levels.

Summarized in this test report are hydraulic conductivity values determined for selected freshwater and saline (attapulgite- or clay blend-based) product formulations permeated with waters of either constant or variable salinity over time.

Methods

Representative samples of selected freshwater (FW) and saline (SW) formulations (n = 1 for each formulation) were permeated with waters of different salinity levels in the laboratory using flexible-wall permeameters (constant head). Testing was conducted in general conformance with ASTM Method D5084, as was freshwater product testing (see Test Report No. 3). Cell pressures during testing ranged from approximately 10 to 40 psi and hydraulic gradients were varied from less than 5 cm/cm to slightly over 30 cm/cm.

Samples tested included a number of selected FW or SW formulations manufactured using different clay types (sodium bentonite, attapulgite, or a clay blend); different clay to aggregate weight ratios (2080 to 5050); and a couple different aggregate sizes and gradations. Additional testing details are provided in Tables 1 and 2.

Permeant (input) salinity values ranged from 0 parts per thousand, ppt (de-aired tap water), up to approximately 36 ppt, which is equivalent to that of typical undiluted, or full-strength, seawater. When testing freshwater formulations, Input salinity values were held constant at 0, 8 to 9, and approximately 18 ppt (Table 1). Values were held constant at approximately 36 ppt when testing saline formulations (Table 2). A commercially available seawater salt mix was used to prepare saline solutions at target levels and a calibrated specific conductance meter (with temperature correction) was used to verify target levels. The chemical composition of the prepared seawater solutions was verified against the known composition of typical seawater.

In addition to conducting flexible-wall permeameter testing, a series of rigid-wall permeameter tests (falling head) were also conducted on several selected formulations using permeants containing variable salinity levels over time. Testing was conducted in general accordance with accepted methodology and procedures. Multiple pore volumes of first full-strength seawater then freshwater were continuously passed through each of several different clay rich formulations (5050 FW, 5050 SW attapulgite, and 5050 SW clay blend) over an approximately 30 to 40-day period. The electrical conductivity of volumes of discharge waters emanating from the base of each column was also tracked during testing.

Results

Flexible-wall permeameter values for selected FW product formulations permeated with waters of different yet constant salinity levels, and at different hydraulic gradients, are presented in Table 1. Values for selected SW formulations permeated with full-strength seawater, also at different gradients, are presented in Table 2.

Results of rigid-wall permeameter testing of different FW and SW formulations using permeants of variable input salinity over time are portrayed in Figures 1 through 3.

Table 1

Hydraulic Conductivity of Selected Freshwater AquaBlok Formulations as a Function of Permeant Salinity and Hydraulic Gradient

Freshwater Product Formulation [1, 2]	Approx. Permeant Salinity (ppt)	Hydraulic Conductivity as a Function of Hydraulic Gradient (in units of cm/cm)						
		<5	5-10	10-15	15-20	20-25	25-30	>30
2080 FW	0	--	--	--	--	8.1×10^{-9} [4]	--	--
	8 [3]	4.0×10^{-8}	5.7×10^{-8}	--	--	--	--	--
	9	--	5.4×10^{-8}	6.6×10^{-8}	--	6.5×10^{-8}	--	6.2×10^{-8}
	18	--	1.0×10^{-6}	1.7×10^{-6}	5.9×10^{-6}	--	6.0×10^{-6}	6.0×10^{-6}
3070 FW	8 [3]	1.3×10^{-8}	1.2×10^{-8}	--	--	--	--	--

Footnotes:
1. “2080 or “3070” indicates relative percentages of clay and aggregate, by dry weight. “FW” indicates a freshwater (sodium bentonite-based) product.
2. Aggregate used to prepare product nominally equivalent in size gradation to AASHTO No. 8 aggregate.
3. Permeant liquid comprised of relatively calcium- and chloride-rich wastewater (I.e. pond water from a specific project).
4. Please see Test Report No. 3 for additional conductivity data derived by permeating fresh water through various FW product formulations.

Table 2

Hydraulic Conductivity of Selected Saline AquaBlok Formulations to Full-Strength (~36 ppt) Seawater as Function of Hydraulic Gradient

Clay Type in Sealant Layer	Saline Product Formulation [1, 2]	Hydraulic Conductivity as a Function of Hydraulic Gradient (units of cm/cm)						
		<5	5-10	10-15	15-20	20-25	25-30	>30
Attapulgite (palygorskite)	3070 SW	5.9×10^{-5}	--	--	3.1×10^{-5}	--	1.4×10^{-5}	--
	4060 SW	--	1.6×10^{-7}	--	3.2×10^{-7}	--	4.0×10^{-6}	--
	5050 SW	--	7.8×10^{-8}	8.6×10^{-8}	--	8.3×10^{-8}	3.1×10^{-7}	--
	5050 SW [3]	--	--	--	7.0×10^{-8}	--	--	--
Clay Blend	3070 SW	--	7.5×10^{-8}	--	7.6×10^{-8}	--	1.0×10^{-7}	--
	5050 SW	--	4.9×10^{-8}	--	4.8×10^{-8}	--	5.3×10^{-8}	--

Footnotes:
1. “5050” or “2080” indicates relative percentages of clay and aggregate, by dry weight. “SW” indicates a saline (attapulgite or clay blend) product formulation.
2. Unless noted otherwise, aggregate used to prepare product nominally equivalent in size gradation to AASHTO No. 8 aggregate.
3. Aggregate core comprises a blend of equal quantities of nominal AASHTO No. 8 and No. 57 aggregate.

Observations and Conclusions

Flexible-Wall Permeameter Testing Results

Although low permeability values (10^{-8} to 10^{-9} cm/s) can be achieved when permeating freshwater formulations with fresh and even brackish waters, higher flow (as high as 10^{-6} cm/s) tends to occur when the same formulations are permeated with higher-saline waters (Table 1). This phenomenon has generally been observed by others (e.g. Stern and Shackelford, 1998; Stewart et al., 2003; Day, 1994) and illustrates the relative sensitivity and physical instability of sodium bentonite (montmorillonite) in higher-saline environments, particularly in terms of the clay’s tendency to flocculate in the presence of high concentrations of salts, which leads to increased effective porosity and, ultimately, increased permeability.

Nevertheless, because permeability values equal to or less than 10^{-7} cm/s are considered appropriate for different types of clay based barriers in a variety of environmental applications (Tobin and Wild, 1986; Sallforg and Hogsta, 2002; US EPA, 1998; Dunn and Palmer, 1994), data in Table 1 also imply that some FW formulations - particularly those relatively enriched in clay – can be used to create appropriate, effective hydraulic barriers in brackish waters with salinity levels of up to at least 8 or 9 ppt. The appropriateness of using FW formulations – rather than SW formulations - to meet project-specific goals in impacted brackish/estuarine, or even wastewater-pond, environments should be evaluated on a project-specific basis.

In contrast to the relative sensitivity of FW formulations to higher saline permeants, the permeability of attapulgite-based materials – particularly those with relatively high clay content – typically remain at or below 10^{-7} cm/s when permeated with full-strength seawater solutions (Table 2). Similarly low permeability values are also seen when attapulgite-based product is permeated with less saline waters, including freshwater (data not shown). The current work also indicates that relatively higher permeability values, up to 10^{-5} cm/s, may occur for less clay rich, attapulgite-based formulations when infiltrated with full-strength seawater (Table 2). Nevertheless, the relative physical and hydraulic insensitivity (stability) of attapulgite-based materials to salts and other chemically aggressive solutions (organic leachates, acidic solutions, etc) - in contrast to the relative sensitivity and instability displayed by many bentonite-based materials to such permeants - has been noted by others (Shackelford, 1994; Galan, 1996; Tobin and Wild, 1986).

Physical loading of saline formulations (during or following hydration) may have a positive influence on reducing barrier permeability by reducing residual porosity through compression or compaction of the hydrating/hydrated material mass (see Test Report No. 9).

As also indicated in Table 2, permeameter values for formulations manufactured using a *blend* of clays and permeated with full-strength seawaters are also relatively low, on the order of 10^{-8} cm/s. Similarly low values were also observed when lower-salinity waters, including freshwater, were used as the permeant (data not shown). However similar, test results for blended formulations (Table 2) appear to differ from results for attapulgite-based formulations in two important respects: (1) values for relatively clay rich, blended formulations (e.g. 5050 SW) appear to be somewhat lower than for similar, attapulgite-based formulations and (2) values for less clay rich, blended formulations (i.e., the 3070 SW formulation) are up to several orders of magnitude lower than for similar, attapulgite-based formulations.

The positive effect that blending attapulgite with sodium bentonite can have on the physical as well as hydraulic stability of environmental barrier materials in high salinity systems and in other chemically aggressive environments has been recognized by others (e.g. Murray 2000; Stern and Shackelford, 1998).

Rigid-wall Permeameter Testing Results

Results of rigid-wall permeameter testing of selected FW and SW formulations generally corroborate results of flexible-wall testing (Figures 1 through 3). Recognized differences in equipment, testing methodologies, etc. usually preclude direct, quantitative comparisons of the two types of data, and it is generally accepted that rigid-wall tests tend to overestimate hydraulic conductivity values (Shackelford, 1994), as also seen herein.

As illustrated through flexible-wall testing, rigid-wall results once again generally reflect the relatively high sensitivity of sodium bentonite-based materials to permeants of variable salinity (Figure 1) in contrast to the relative insensitivity, or stability, of attapulgite-bearing materials to the same, temporally variable permeants (Figure 3). Blended clay formulations tend to display an intermediate hydraulic response (Figure 2).

To summarize, attapulgite- or blended clay based formulations of the AquaBlok product are as appropriate for use within saline environments as are bentonite-based formulations for use at freshwater sites. And although not typically applicable to higher salinity environments, some bentonite-based formulations can also be effective in some brackish environments. The level of appropriateness will depend on a number of factors (spatial and temporal ranges in salinity values; prevailing surface-water salinity

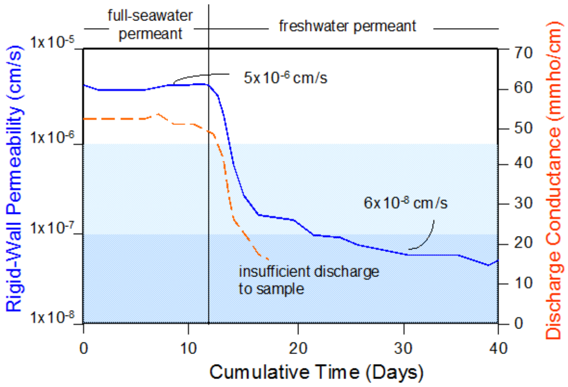

Figure 1. Testing of 5050 FW (poorly graded)

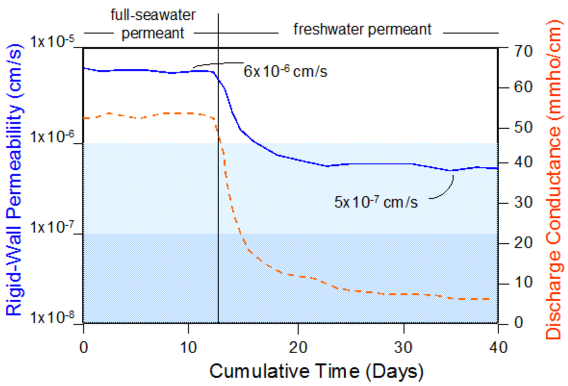

Figure 2. Testing of 5050 SW Clay Blend (poorly graded)

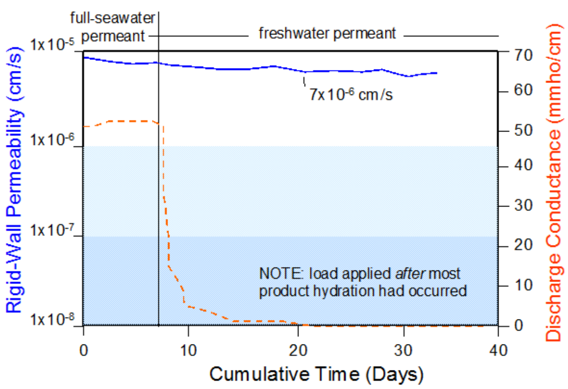

Figure 3. Testing of 5050 SW Attapulgite (poorly graded)

values during product placement; target cap thickness; etc.) and should be evaluated on a case by case basis.

Furthermore, if achieving a particular, target permeability value is a primary goal for remedial cap performance at a specific saline site, then the most appropriate saline formulation for use in the project could involve a number of additional considerations, including: allowable tolerance range for meeting the target value; an understanding of the relationship between water-column salinity and water depths, including whether or not a significant salt wedge periodically occurs at the site and when/where the wedge occurs; target cap design and relative product costs; etc.

Material Selection

Results presented herein indicate that blended clay formulations (rather than attapulgite-based product) are probably more appropriate for use in sediment cap designs for most full-seawater environments; surcharging with sand or aggregate loads, either during or after product hydration, may help consolidate barrier material and increase its ultimate effectiveness. Relatively clay rich, attapulgite-based formulations may also be effective in some full-seawater systems, and could be more appropriate than blended product for use in other chemically aggressive environments, depending on the dissolved or pure-phase contaminants involved.

The laboratory data and literature presented herein also imply that, although sodium bentonite-based product is not usually appropriate for typical full-seawater environments, it could, in fact, be effective and appropriate for barrier construction in estuarine environments, where significant spatial and temporal variability exists in salinity levels, and where adequate "windows" of less saline (and more brackish) waters may occur during which the freshwater product could be applied. The appropriateness of applying sodium bentonite-based product in saline or brackish environments should be evaluated on a case by case basis.

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Last Revised 02/22/2016