Hydraulic conductivity of sand admixed with processed clay mixtures

Conductivité hydraulique du sable ajouté à des mélanges d'argiles traitées

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ABSTRACT: The results of a laboratory test program designed to evaluate the hydraulic conductivity of compacted test specimens of sand-bentonite, sand-attapulgite clay, and sand-bentonite-attapulgite clay mixtures at clay soil contents of 10, 15, and 20 percent are presented. The results indicate that the hydraulic conductivity, k, of compacted test specimens decreased as the clay soil content increased from 10 to 20 percent. Also, the greater swelling potential associated with bentonite relative to attapulgite clay resulted in a more rapid decrease in k with increase in clay soil content for the sand-bentonite mixtures and the sand-bentonite-attapulgite clay mixtures relative to the sand-attapulgite clay mixtures. Finally, the amount of clay soil required to achieve $k \leq 10^{-7}$ cm/s for the sand-clay soil mixtures increases as the attapulgite clay content in the admixture increases.

RESUME: Les résultats d'un programme de test en laboratoire conçu pour évaluer la conductivité hydraulique d'échantillons tassés de mélanges d'argile avec sable et bentonite, d'argile avec sable et attapulgite, d'argile avec sable, bentonite et attapulgite à teneur d'argile de 10, 15 et 20 pour cent sont présentés ici. Les résultats indiquent que la conductivité hydraulique, k, des échantillons tassés diminue à mesure que la teneur en argile augmente de 10 à 20 pour cent. En outre, le potentiel de gonflement considérable associé à la bentonite par rapport à l'argile attapulgite a eu comme conséquence une diminution plus rapide en k avec l'augmentation de la teneur en argile pour les mélanges sable-bentonite et les mélanges d'argile avec sable, bentonite et attapulgite par rapport aux mélanges d'argile avec sable et attapulgite. Enfin, la quantité d'argile nécessaire à l'obtention de $k \leq 10^{-7}$ cm/s pour les mélanges d'argile et de sable augmente à mesure que la teneur en argile attapulgite de l'adjuvant augmente.

1 INTRODUCTION

Compacted sand-bentonite mixtures have been used as low-permeability liners for waste containment systems in cases where suitable natural clayey soils are not readily or economically available (e.g., Garlanger et al. 1987, Chapuis 1992, and O'Sadnick et al. 1995). The use of a processed bentonite, typically sodium bentonite, in the mixture usually is justified on the basis of the ability to achieve a relatively low hydraulic conductivity (e.g., $\leq 10^{-7}$ cm/s) upon permeation with water using only relatively small quantities of the bentonite admixture. For example, Garlanger et al. (1987) found that only 6 percent of a heavily polymerized sodium bentonite (liquid limit, LL = 950%, plasticity index, PI = 918%) was required to achieve a hydraulic conductivity, k, $\leq 10^{-8}$ cm/s based on laboratory tests when the bentonite was mixed with a borrow sand containing from 3 to 4 percent fines. O'Sadnick et al. (1995) reported $k \leq 10^{-7}$ cm/s for compacted mixtures containing only 9 percent of a powdered sodium bentonite mixed with a poorly graded sand (USCS = SP). These low hydraulic conductivity values for compacted sand-bentonite mixtures are attributed primarily to the high swelling potential of sodium bentonites in the presence of water resulting in the formation of a relatively "tight" soil matrix.

However, studies also have shown that the hydraulic conductivity of compacted sand-bentonite mixtures permeated with an actual or simulated waste liquid or leachate can be significantly higher than the hydraulic conductivity of the same mixtures permeated with water. For example, Gipson (1985) reports that the measured k values of compacted sand-bentonite mixtures containing 7.5, 10, and 15 percent bentonite permeated with an acid leachate (pH = 2.2) containing metals increased by approximately 7, 13, and 41 times, respectively, over a one-year period relative to the initial hydraulic conductivity based on water permeation. Shackelford (1994) reported that the hydraulic conductivity of compacted sand-bentonite mixtures containing 16 percent sodium bentonite was 2.7×10^{-8} cm/s when permeated with tap water but increased to 1.6×10^{-5} cm/s, or approximately 600 times higher, when permeated with a calcium saturated tailings solution. In both of these cases, the incompatibility between the sand-bentonite mixtures and the waste liquids resulted in decisions not to use the compacted sand-bentonite mixture as a waste containment liner.

The large increases in k of natural soils admixed with bentonite are attributed to the relatively high reactivity of bentonite soils in the presence of chemical solutions. For example, Ryan (1987) reports results of relative filtrate loss tests that indicated the flow rate using the actual contaminated ground water containing several organic solvents (e.g., phenols, acetone, benzene, toluene, xylene, and gasoline) reached approximately 3 and 5.5 times the flow rate with tap water after about three pore volumes of flow for bentonite and treated bentonite slurries, respectively. The large increases in flow rates were attributed to cracking of the bentonite due to shrinkage in the presence of the organic solvents. Day (1994) reports similar results for bentonite and treated bentonite slurries permeated with a brine water leachate.

As a result of the incompatibility between some waste liquids and bentonite, some studies have evaluated the use of other processed clay soils as admixture materials for waste containment applications. In particular, attapulgite clay consisting primarily of the chain-structured clay mineral, attapulgite, has been considered for use as a substitute for bentonite in vertical cutoff walls as well as in compacted clay liners (e.g., Tobin and Wild 1986, Ryan 1987, Broderick and Daniel 1990, and Day 1994). These studies have shown that the hydraulic conductivity of compacted attapulgite clay and attapulgite clay slurries is relatively unaffected when permeated with several different waste liquids.

A qualitative comparison of the properties of attapulgite clay and bentonite is provided in Table 1. In general, attapulgite crystals are needle-like resulting in aggregates that form a "hay stack" structure. The attractive forces between the needles within a particle are considerable and, therefore, attapulgite is not particularly susceptible to swelling. However, attapulgite is a highly sorptive material in terms of absorption of water into the channels between the crystals. Attapulgite clay also appears to be stable in high concentrations of electrolytes and, therefore, is not as susceptible as the plate-like clay minerals to dramatic changes in k after exposure to liquid waste (Tobin and Wild 1986). As a result, attapulgite clay may be used as a soil additive to help

Table 1. Characteristics of attapulgite and bentonite clays (after Tobin and Wild 1986).

Clay Characteristic	Type of Clay	
	Attapulgite	Bentonite
Principal Mineral	attapulgite	montmorillonite
Crystal Structure	chain	three-layer sheet
Particle Shape	needle	plate
Surface Area	high	medium
Swell Potential	low	high
Cation Exchange Capacity	low	high
Effect of Electrolytes	slight	flocculates
Sorptivity	high	medium

Table 2. Physical properties of soil constituents.

Property	ASTM Test Standard	Soil Constituent		
		Attapulgite Clay	Granular Bentonite	Silica Sand
Liquid Limit, LL (%)	D 4318	305	405	--
Plasticity Index, PI (%)	D 4318	209	367	NP
Specific Gravity, G_s	D 854	2.71	2.87	2.66
Percent Sand (0.074-4.75 mm)	D 421	6.5	5.0	100
Percent Silt (0.002-0.074 mm)	D 422	29.0	20.0	0
Percent Clay (< 0.002 mm)	D 422	64.5	75.0	0
USCS	D 2487	CH	CH	SP

NP = Non-plastic

Table 3. Chemical properties of soil constituents.

Property	Soil Constituent		
	Attapulgite Clay	Granular Bentonite	Silica Sand
Cation Exchange Capacity, CEC (meq/100 g)	18.1	63.9	NA
Exchangeable Metals (meq/100 g):			NA
Ca	5.9	18.6	
Mg	11.1	7.4	
Na	0.1	29.8	
K	0.3	1.3	
Al	<0.1	<0.1	
Si	0.2	1.0	
Sum	17.6	58.1	NA
Soil pH (1:1 paste)	9.7	9.1	8.5

NA = Not Applicable

stabilize an otherwise unstable soil. However, since the high swelling potential evident in sodium bentonite is not evident in attapulgite clay due to the difference in mineralogical composition of the soil, the primary concern with the use of attapulgite clay as a liner material is the ability to achieve a relatively low hydraulic conductivity when permeated with water.

Although attapulgite clay has been used in soil barriers, the potential use of attapulgite clay as a substitute, either wholly or partially, for bentonite in compacted sand-bentonite mixtures used for waste containment liners has not been evaluated. The initial stage of such an evaluation is to determine whether mixtures of sand and attapulgite clay can achieve suitably low hydraulic conductivity values upon permeation with water. Accordingly, the results of a laboratory test program designed to measure the hydraulic conductivity of mixtures of a sand with two processed clay soils - a granular sodium bentonite and an attapulgite clay - when permeated with water are presented in this paper. The purposes of the laboratory test program are (1) to evaluate the feasibility of achieving relatively low k values of compacted specimens consisting of each processed clay soil mixed with a sand, and (2) to establish baseline hydraulic conductivity values of combinations of the two processed clay soils mixed with the same sand. The results serve to provide a preliminary indication of the expected behavior of alternative sand-attapulgite clay and sand-attapulgite clay-bentonite soil mixtures upon permeation with simulated or actual leachates.

2 MATERIALS AND METHODS

2.1 *Soil constituents*

The soil constituent materials used in this study are attapulgite clay, granular bentonite, and sand. The attapulgite clay was obtained from the Floridin Company, Quincy, Florida, and is known commercially as Microsorb-ES. The granular bentonite was obtained from WyoBen, Inc., Billings, Montana, and is known commercially as Bighorn-10 Bentonite. The silica sand was obtained from the Colorado Lien Company in LaPorte, Colorado. Some physical and chemical properties of the soil constituents are provided in Tables 2 and 3, respectively. Approximately 51 percent of the exchange complex of the granular bentonite is occupied by sodium and, therefore, the bentonite is categorized as a sodium bentonite although an appreciable amount of the exchange complex is occupied by calcium (32%) and magnesium (13%).

2.2 *Soil mixtures*

Three sand-clay soil mixtures were used in this study: sand mixed with attapulgite clay, sand mixed with bentonite, and sand mixed with a mixture of attapulgite clay and bentonite. Each sand-clay soil mixture was evaluated for total clay soil contents of 10, 15 and 20 percent (dry weight basis). In this context, "clay soil content" refers to the total amount of attapulgite clay and/or bentonite in the soil mixture which is distinguished from the "clay particle content" that refers to the amount of clay particles (e.g., % < 2 μm) in the soil mixture. The clay soil content of the sand-clay soil mixture containing both bentonite and attapulgite clay was composed of equal amounts of the two processed clay soils (i.e., 50% each by dry weight of the clay soil portion).

The minimum clay soil content of 10 percent was based primarily on the results of the study by Kenney et al. (1992) who found that many void spaces did not contain bentonite for bentonite contents ≤ 7 percent due to inadequate distribution during mixing. Instead, Kenney et al. (1992) found that adequate distribution of the bentonite in the mixture occurred for bentonite contents ≥ 9 percent which is reasonably consistent with the use of bentonite contents of 10, 7.5, and 9 percent reported by Lundgren (1981), Garlanger et al. (1987), and O'Sadnick et al. (1995), respectively, based on a field mixing criterion.

The soil mixtures were prepared for compaction by mixing the appropriate amount of a processed tap water (pH = 7.1 with ionic strength of ~ 4 x 10^{-4} M) with the sand followed by mixing the clay soil in stages with the wetted sand by hand using a spoon. After the clay soil, sand, and water were mixed, the sample was placed in double Zip-Loc® plastic bags and cured for 24 hours. For the mixtures containing both clay soils, the air-dried clay soils were mixed together in a large batch such that equal amounts (dry weight basis) of each clay soil resulted, and the appropriate amount of the mixed clay soil was taken from the batch and added to the wet sand. The cured mixtures were compacted according to the standard compaction procedure (ASTM D 698). The maximum dry unit weights, γ_{dmax}, and optimum water contents, w_{opt}, for each mixture are presented in Table 4.

2.3 *Hydraulic conductivity tests*

Flexible-wall (FW) hydraulic conductivity tests were used to determine hydraulic conductivities for compacted test specimens of each mixture in accordance with procedures described in ASTM D 5084 (Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter). The FW test apparatus is similar to the one described by Daniel et al. (1984). The falling-headwater/rising-

Table 4. Compaction properties of sand-clay soil mixtures.

No.	Clay Soil Content (% dry weight)			Compaction[1] (ASTM D 698)	
	Attapulgite Clay	Granular Bentonite	Total	γ_{dmax} kN/m^3 (pcf)	w_{opt} (%)
1	10	0	10	16.09 (102.5)	16.0
2	15	0	15	15.86 (101.0)	16.5
3	20	0	20	15.70 (100.0)	20.0
4	0	10	10	16.08 (102.4)	18.0
5	0	15	15	16.12 (102.7)	15.0
6	0	20	20	16.09 (102.5)	14.5
7	5	5	10	16.05 (102.2)	17.5
8	7.5	7.5	15	15.94 (101.5)	16.0
9	10	10	20	15.86 (101.0)	15.5

[1] γ_{dmax} = maximum dry unit weight; w_{opt} = optimum water content.

tailwater procedure was used (ASTM D 5084). Analysis of data for this particular type of flexible-wall test is found in Daniel (1989). All hydraulic conductivity tests for test specimens of the sand-clay soil mixtures were duplicated; thus, a total of 18 FW tests were performed for the 9 soil mixtures. In addition, the hydraulic conductivity of the sand was measured.

Each test specimen was compacted in accordance with ASTM D 698 at a water content between one and three percentage points wet of w_{opt}. The compacted specimens were extruded from the compaction molds, assembled in the FW apparatus, and back-pressured to achieve an average effective stress of 34.5 kPa (5 psi) upon saturation. After back-pressure saturation, the headwater pressure was increased by 17.2 kPa (2.5 psi) and the tailwater pressure was decreased by 17.2 kPa (2.5 psi) to maintain an average effective stress of 34.5 kPa (5 psi). Flow was from the bottom to the top of the test specimen.

The assembled test specimens were permeated with the same processed tap water used in compaction. The applied hydraulic gradient ranged from 32.5 to 28.1 as the water level in the headwater accumulator decreased and the water level in the tailwater accumulator increased. However, the average hydraulic gradient never exceeded 30.3 in all tests. This average hydraulic gradient meets ASTM D 5084 requirements for soils with hydraulic conductivities $\leq 10^{-7}$ cm/s. The criterion used to determine test completion was steady-state hydraulic conductivity. The permeation stages of the hydraulic conductivity tests ranged from 1.2 to 6.7 hours for the sand-attapulgite clay test specimens with 10 and 15 percent clay soil contents, and from 34.5 to 180 days for all other tests. Further details of the materials and methods are provided by Howell (1996).

3 RESULTS AND DISCUSSION

The results of all flexible-wall k tests, shown in Fig. 1, indicate that the measured k values for all mixtures with a given clay soil admixture decrease with increasing clay soil content. However, the decrease in k for mixtures containing bentonite is significantly more rapid than the mixtures containing only attapulgite clay as the admixture. This difference in the observed rate of decrease in k can be attributed to the higher swelling potential of bentonite relative to attapulgite clay (e.g., see Table 1). Thus, the bentonite is able to fill voids more effectively at lower clay soil contents than the attapulgite clay due to the greater swelling potential of the bentonite. As a result, a significantly greater attapulgite clay content is required for the sand-attapulgite clay mixtures to achieve a relatively low hydraulic conductivity than is required for the sand-bentonite mixtures. For example, in this study, approximately 20 percent attapulgite clay content is required to achieve $k \leq 10^{-7}$ cm/s, whereas 10 percent bentonite content is more than sufficient to achieve $k \leq 10^{-7}$ cm/s.

As expected, the k values for the mixtures containing both attapulgite clay and bentonite lie between the k values for the mixtures containing only attapulgite clay and the mixtures containing only bentonite. However, the trend of decreasing k with increasing clay soil content for the mixtures containing both attapulgite clay and bentonite is closer to the same trend for mixtures containing only bentonite. Thus, the bentonite in the attapulgite clay-bentonite admixture apparently dominates the behavior of the sand-clay soil mixtures in terms of hydraulic conductivity. This observation may be particularly important in terms of evaluating the compatibility of sand-bentonite-attapulgite clay mixtures in that the potentially beneficial aspects of the attapulgite clay may be offset by the dominating behavior of the more reactive bentonite component of the admixture. However, this hypothesis can be verified only by performing compatibility tests with actual or simulated leachates.

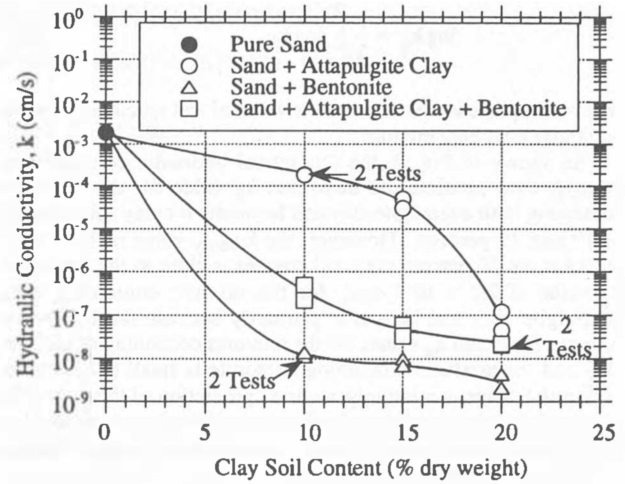

Figure 1. Results of flexible-wall hydraulic conductivity tests for sand-clay soil mixtures.

The dominance of bentonite in the mixtures containing both attapulgite clay and bentonite is illustrated further in Fig. 2 where the geometric mean k values, k_g, measured for the mixtures containing both attapulgite clay and bentonite are compared with the predicted geometric mean values, k_{theory}, for the same mixtures calculated using the following equation (Isaaks and Srivastava 1989):

$$\log\left(k_{theory}\right) = \frac{1}{2}\sum_{j=1}^{2}\log\left(k_{gj}\right) \qquad (1)$$

where k_g is the geometric mean hydraulic conductivity of the duplicate tests for a given clay soil admixture and a given clay soil content (i.e., k_{g1} is the geometric mean k value for the sand-attapulgite clay mixture and k_{g2} is the geometric mean k value for the sand-bentonite mixture at the same clay soil content) calculated in accordance with the following equation:

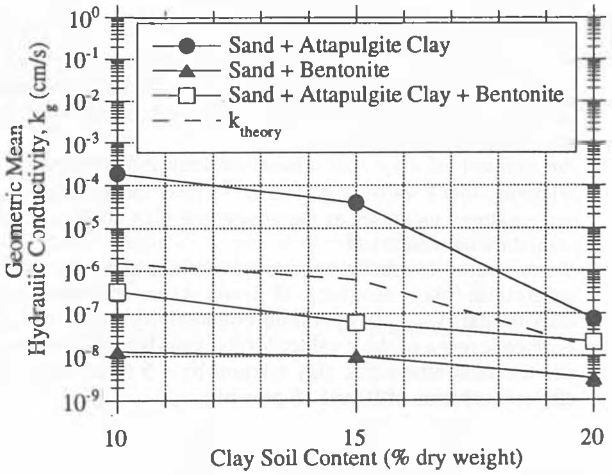

Figure 2. Measured and predicted (k_{theory}) geometric mean hydraulic conductivity as a function of clay soil content.

$$\log k_g = \frac{1}{2}\sum_{i=1}^{2}\log k_i \qquad (2)$$

where k_i represents the measured k value of test specimen i for the particular sand-clay mixture.

As shown in Fig. 2, the theoretical hydraulic conductivity, k_{theory}, over predicts the measured k_g value for the mixtures containing both attapulgite clay and bentonite for clay soil contents of 10 and 15 percent. However, the k_{theory} value of 1.5×10^{-8} cm/s for the 20 percent clay soil content is close to the measured k_g value of 2.0×10^{-8} cm/s for the mixture containing both attapulgite clay and bentonite primarily because the difference between measured k_g values for the mixtures containing attapulgite clay and the mixtures containing bentonite is small ($\Delta k_g = 6.7 \times 10^{-8}$ cm/s). Thus, a relatively accurate prediction of the hydraulic conductivity of sand-clay soil mixtures with both attapulgite clay and bentonite using Eq. 1 is likely only at relatively large clay soil contents (i.e., $\geq$ 20 percent).

As indicated by the plots in Figs. 1 and 2, the amount of clay soil admixture required to achieve a relatively low k value (e.g., $k \leq 10^{-7}$ cm/s) for the compacted sand-clay soil mixtures increases as the attapulgite clay content in the admixture increases (or decreases as the bentonite content in the admixture decreases). Thus, the potential benefit of increased chemical compatibility by substituting attapulgite clay for bentonite in compacted sand-clay soil mixtures probably will be realized with clay soil contents that are greater than typically required for sand-bentonite mixtures.

The hydraulic conductivity, k_g, of 2.2×10^{-8} cm/s for the mixture containing both 10 percent attapulgite clay and 10 percent bentonite is slightly higher than the hydraulic conductivity, k_g, of 1.3×10^{-8} cm/s for the mixture containing 10 percent bentonite. This implies that the attapulgite clay actually may have an adverse effect on the hydraulic conductivity of the mixtures containing both attapulgite clay and bentonite when evaluating k based on permeation with water. Nonetheless, the measured k_g of 2.2×10^{-8} cm/s for the mixture containing both 10 percent attapulgite clay and 10 percent bentonite still is significantly lower than the typical regulatory limit of $k \leq 10^{-7}$ cm/s, and the slight increase in k_g due to the attapulgite clay content may be a small price to pay for the potential beneficial aspects of the attapulgite clay in terms of an increase in compatibility upon permeation with simulated or actual leachates. However, the potential beneficial aspect of increased compatibility due to the attapulgite clay can be verified only by performing the appropriate compatibility tests.

4 CONCLUSIONS

The following conclusions are drawn from this study:

- the hydraulic conductivity, k, of compacted test specimens of sand-bentonite, sand-attapulgite clay, and sand-bentonite-attapulgite clay mixtures decreased as the clay soil content increased from 10 percent to 20 percent;
- the greater swelling potential associated with bentonite relative to attapulgite clay resulted in a more rapid decrease in k with increase in clay soil content for the sand-bentonite mixtures and the sand-bentonite-attapulgite clay mixtures relative to the sand-attapulgite clay mixtures;
- the amount of clay soil admixture required to achieve a relatively low k value (e.g., $k \leq 10^{-7}$ cm/s) for the sand-clay soil mixtures increases as the attapulgite clay content in the admixture increases; and
- the measured hydraulic conductivity of the sand-bentonite-attapulgite clay mixtures is lower than the predicted (theoretical, k_{theory}) hydraulic conductivity based on the geometric mean of the k values for the sand-bentonite mixture and the sand-attapulgite clay mixture by ~ 5 to 10 times for clay soil contents of 10 and 15 percent.

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