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Effect of methanol and seepage control in permeable kaolinite soil

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Abstract

In this laboratory study, the effects of pure methanol on the behavior of kaolinite clay and clay-sand mixture and methods to reduce the hydraulic conductivity of these soils were investigated. Also consolidation properties of clay and clay-sand mixture were evaluated up to a pressure of 3.2 MPa. The hydraulic conductivity of a kaolinite clay-sand mixture (hydraulic conductivity > 10^{-5} cm/s) could be reduced to far below 10^{-7} cm/s (U.S. EPA limit for soil barriers) by permeating it with grout solutions with viscosity less than 2 mPa·s. The concentration of sodium silicate in the grout solution was varied up to 8%, while the solids content in the cement and bentonite grouts was varied up to 0.3%. Also, the contributions of additives, such as Portland cement (Type 1) and bentonite, in reducing the hydraulic conductivity of clay and clay-sand mixture were investigated. The hydraulic conductivity of soils and the changes due to treatment are related to the plasticity index of the soils. Cement and bentonite (6% by weight) can be used as additives to effectively reduce the hydraulic conductivity of kaolinite clay and clay-sand mixture, respectively.

Introduction

There is increasing concern over the behavior of contaminated permeable soils and controlling seepage of pollutants by treating these soils *in situ*. It is also interesting to evaluate the potential of permeable (site) soils after treatment as impermeable barriers in hazardous waste disposal facilities. In the U.S. the Environmental Protection Agency (U.S. EPA) estimated that about 250 million tons of hazardous wastes are produced each year, of which over one third is disposed in landfills and surface impoundments [1]. Solid waste landfills and liquid waste impoundments are generally underlain by compacted and/or natural soil liners to contain hazardous wastes. Since hydraulic onductivity controls the velocity and volume of fluid flow through soil, both natural and compacted, it is the primary criterion used in evaluating the suitability of earthen liners for containing hazardous wastes. The U.S. EPA currently requires that the hydraulic conductivity of soil liners for waste disposal be not greater than 10^{-7} cm/s [2].

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A study of 39 hazardous waste sites, revealed that they leaked after an average of 14 years [3]. This finding emphasizes the need for long-term performance (consolidation) studies on soil barriers. When these waste sites were repaired, only 16% of the effort was totally successful, and some 43% of the repairs failed totally [3]. These observations emphasize the need to improve methods for repairing existing leaks in contaminated soil liners in order to satisfy the U.S. EPA's hydraulic conductivity requirement. If *in situ* treated permeable soils could satisfy the U.S. EPA requirement of 10^{-7} cm/s of hydraulic conductivity, these treated soils could be used as soil barriers for future waste disposal facilities, leading to substantial economic benefits. By using a deflocculant, sodium tripolyphosphate (STP), the hydraulic conductivity of permeable clay was reduced, and used successfully as a barrier for a waste disposal site [4]. Local clay or local soil–bentonite mixtures are commonly used to line surface impoundments or hazardous waste landfills [4–13]. But there is only limited information available in the literature on the behavior of contaminated soils and their treatability in controlling seepage. Also, the use of clay–sand mixtures instead of pure clays as soil barriers is increasing because of economic benefits, ease of handling and better mechanical properties.

Although several investigators have shown that concentrated organic chemicals can alter the structure of compacted clays (develop shrinkage stresses and shrinkage cracks) and increase its hydraulic conductivity [6,8,12–22], very little is known about reducing the hydraulic conductivity of soil contaminated with organic hazardous permeant. Because permeant contaminated soils are encountered in the field more frequently, it is of special interest to investigate their behavior, and also the feasibility of treating them *in situ* to reduce their hydraulic conductivity [23–28]. This paper discusses laboratory tests, observations, treatment results and correlations between contaminated soil properties.

Objectives

The objectives of this study were (a) to investigate the effect of methanol on the behavior of kaolinite clay and clay–sand mixture, and (b) to determine the effectiveness of additives and grouts in reducing the hydraulic conductivity of permeable clays contaminated with and without methanol.

Experimental program and results

The testing program was structured to provide an effective means of comparing the behavioral characteristics of clay and clay–sand mixture in the presence of water and methanol and to investigate the possibility of reducing the hydraulic conductivity of permeable clays *in situ* in order to satisfy the U.S. EPA limit of 10^{-7} cm/s. This study was limited to kaolinite clay and a representative organic hazardous permeant. The kaolinite clay, consisting mostly of kaolinite mineral, has been used extensively by other researchers in laboratory studies [5,6,13,15,27]. The specific gravity of kaolinite solids (ASTM D 854) was determined to be 2.59. Using a centrifuge method, the kaolinite particles were determined to be finer than 0.075 mm, but 70% (by weight) were less than 0.002 mm (clay fraction), as shown in Fig. 1. A well graded blasting sand was used to prepare clay–sand mixtures to represent permeable soils. Blasting sand is mainly quartz and is available commercially with particle sizes, ranging between sieve no. 4 (4.75 mm) and 200 (0.074 mm) (Fig. 1) as determined by ASTM D 422. In this investigation, a mixture of kaolinite clay and blasting sand (kao/sand) was used by varying the sand content up to 70% by weight. Because methanol has been used extensively in previous studies, comparison of the test results was possible [8,13,17–20]. Hence, methanol was selected as the organic-waste permeant. Methanol is also listed as a CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act) hazardous substance, and as a toxic chemical [2]. Pure methanol has a dielectric constant of 33.6, (water has a dielectric constant of 80.4), which can reduce the thickness of the diffusion double layer that surrounds the clay particles. This in turn causes flocculation of particles, and may produce shrinkage cracks that lead to increased hydraulic conductivity [6,8,16]. Interaction between methanol and kaolinite clay was also studied using sedimentation analysis and index limits (also known as Atterberg limits) tests. The effect of methanol contaminated pore fluid on the long-term stability of the clay and clay–sand mixture was studied using odeometers. To obtain the baseline information on the behavior of clay and clay–sand mixture, water was used as a standard permeant.

The effect of additives and grouts in controlling seepage in clay and clay–sand mixture was also studied. The additives and grouting materials selected for this study were bentonite (sodium-based), Portland cement (Type I), and sodium silicate. The grouts were dilute solutions (concentrations varied from

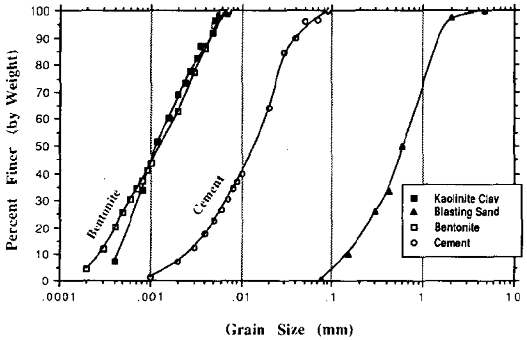

Fig. 1. Particle size distribution.

0.05% to 8%), and the additives were varied up to 6% by weight of soil. The grouts were characterized according to their initial (dynamic) viscosity, pH, and changes in viscosity over time. Because bentonite is a very highly plastic and swelling clay material, and is composed primarily of sodium-montmorillonite minerals, it has the potential of swelling to 15 to 20 times its volume when wet [23,24]. The sodium bentonite used in this study has a plastic limit of 57% and a liquid limit of 545%. The particle-size distribution of the bentonite used in this study is similar to that of kaolinite clay (Fig. 1). A Capa-700 series (manufactured by Horiba) particle size analyzer was used to determine the particle size of cement, bentonite, and kaolinite samples. The particle size analyzer uses a method of sedimentation (both the gravity and centrifuge options are available) and measures a relative absorbence/transmission at regular intervals to determine the particle size in the range of 0.05 to 300 μm. The results reported in Fig. 1 are the average of three tests. Cement particle size varied from 0.8 to 100 μm, while kaolinite and bentonite particle sizes ranged of 0.1 to 6 μm. The two shape parameters that are generally used to describe the particle size distribution curves are the coefficient of uniformity ($C_u = D_{60}/D_{10}$) and the coefficient of concavity ($C_c = D_{30})^2/D_{60}D_{10}$). The coefficients of concavity and uniformity for cement and bentonite were 7 and 6.4, and 1.09 and 0.65, respectively. Due to the alkalinity of cement pH of 0.1% and 0.3% cement grout solutions were 10.6 and 11.1, respectively. The pH of 0.1% and 0.3% bentonite solutions was 7.8. Also, sodium silicate, N-grade with 3.2 silica/alkali ratio, was used up to a solution concentration of 8%. The pH of the 8% sodium silicate solution was 10.5.

Using a cylindrical-spindle-type viscometer (Brookfield viscometer), the changes in viscosity were studied up to 2 hours for various concentrations of cement, bentonite, sodium silicate grout solutions and their mixes, according to ASTM D 4016. Also, the viscosity was measured at different rates of shearing (spindle speeds of 1.5, 6 and 30 rpm). The overall change in viscosity with time and shearing speed was small; that is, it varied within the range of 0.8 to 1.5 cP or mPa·s (close to the viscosity of water). The low concentrations of cement and bentonite did not have much influence on the viscosity of water. When cement was mixed with water (only), no settlement (total suspension) was observed for 2 hours, but sodium silicate accelerated the settling of cement particles in the solution. Also, 8% sodium silicate solution could increase the pH of 0.1% ad 0.3% bentonite solutions to 10.5 and 11.1, respectively. The addition of 8% sodium silicate to 0.1% or 0.3% cement solutions resulted in a pH of 11.2.

Compaction

Compaction is a common practice in the construction of soil liners because it is a means of improving mechanical properties an reducing hydraulic conductivity. Elsbury et al. [25] demonstrated the importance of compacting wet of optimum water content (corresponding to maximum dry unit weight) for soils to obtain the lowest possible hydraulic conductivity. If the soil is compacted dry of optimum water content, it could result in highly permeable soil. Selected soils were compacted according to ASTM D 698 before permeating with water and methanol. The soil moisture content and corresponding dry unit weight were measured and the compaction curves for kaolinite clay and clay–sand mixtures are shown in Fig. 2. The optimum water content and the corresponding maximum dry unit weight (maximum γ_d) for the kaolinite clay were 34% and 83.1 pcf (13.05 kN/m^3), respectively. The optimum water content and maximum γ_d for the 30/70 clay–sand mixture was determined to be 12.2% and 124.2 pcf (19.5 kN/m^3), respectively. Addition of sand decreased the optimum water content but increased the maximum γ_d resulting in reduced void ratio (defined as the ratio of void volume to solid volume). The optimum water content and maximum γ_d for clay with 6% bentonite were 35% and 81.2 pcf (12.8 kN/m^3), respectively. The optimum water content and maximum γ_d with 6% cement were 34.3% and 84.4 pcf (13.3 kN/m^3), respectively. With additives, the optimum water content for compacting kaolinite clay increased, resulting in changes in maximum γ_d.

Sedimentation analysis

This method was used as a quick indicator to verify the concentration of methanol which adversely affected the behavior of kaolinite clay. According to the Gouy–Chapman theory, the low dielectric constant of organic chemicals reduces the thickness of the diffusion double layer that surrounds the clay particles, which in turn causes flocculation of particles and may produce shrinkage cracks that lead to increased hydraulic conductivity. Past studies have shown that if an organic liquid does not affect sedimentation characteristics, the liquid will not affect the hydraulic conductivity of compacted clay [6]. Experience has shown that two hours of sedimentation was adequate for

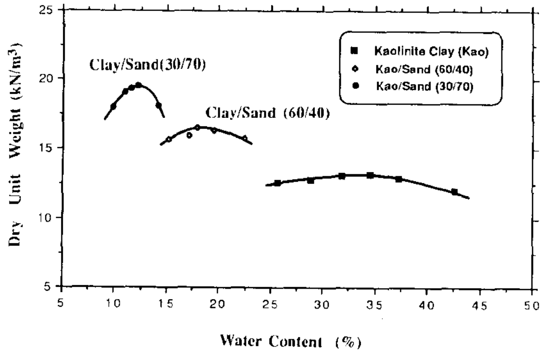

Fig. 2. Dry density–moisture content relationships for clay and clay–sand mixture.

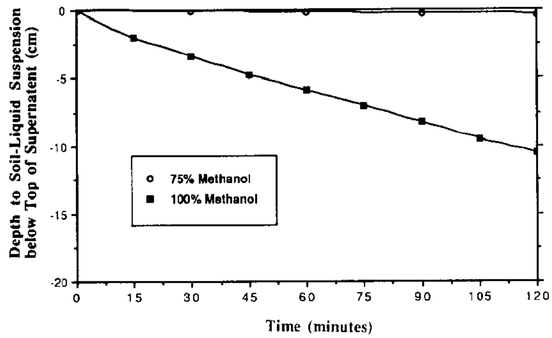

Fig. 3. Sedimentation analysis for Kaolinite clay with methanol.

observing the effect of an organic liquid on the settling velocity of soil particles [6]. Sedimentation measurements of flocculation of clay particles were performed according to ASTM D 422 (Particle Size Analysis for Soils) using various concentrations of methanol. During the tests, hydrometer was not used, but instead the distance from the top of supernatent to the soil–liquid suspension was continuously monitored. Sedimentation tests were performed for various concentrations of methanol (0, 25%, 50%, 75% and 100%). As shown in Fig. 3, for a period of 2 hours, sedimentation was not significant until the methanol concentration was 75%. Pure methanol (100%) caused the soil particles to flocculate the most and to settle out of suspension in just a few minutes, and hence has the potential of affecting the hydraulic conductivity clay. Flocculation of particles was attributed to the low dielectric constant of methanol, which reduced the diffuse double layer in the clay particles.

Index limits

The purpose of the index test is to provide a simple, fast and economical means to achieve a preliminary understanding of permeant-soil and grout (or additive)-soil interactions. The index (Atterberg) limits for kaolinite clay and clay–sand mixture were determined using water, sodium silicate (8% solution in water), additives and pure methanol, according to ASTM D 4318. Earlier studies have shown that the index limits tests can correlate closely with the degree to which a particular organic liquid affects the hydraulic conductivity of compacted clay [6,16].

Clay

Based on the test results, with water and pure methanol, kaolinite clay was classified as MH (inorganic silt) according to the Unified Soil Classification System (USCS) [28]. Pure methanol increased the liquid limit and plastic limit of kaolinite clay but reduced the plasticity index from 24 (with water) to

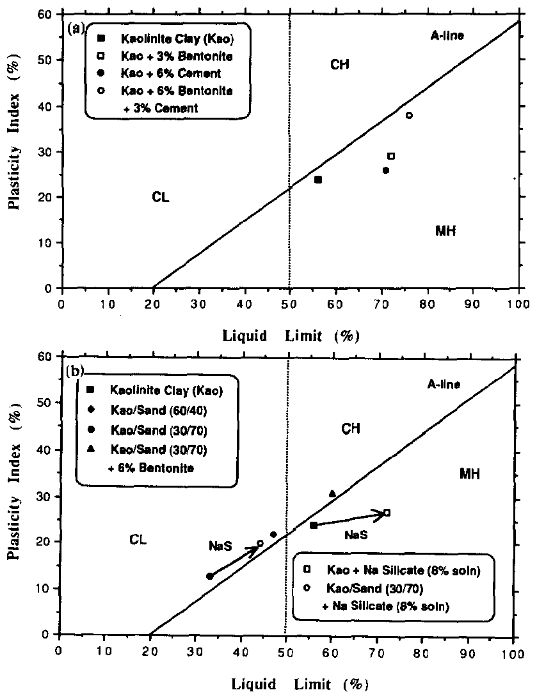

Fig. 4. Plasticity Chart for soils with additives and grout solution.

20. The plasticity index is equal to the difference between the liquid limit and the plastic limit of the soil and represents the range within which the soil is plastic. The liquid limit, plastic limit, and plasticity index of kaolinite clay increased when 8% sodium silicate (abbreviated as NaS) solution was used, as shown in Fig. 4. With 6% bentonite additive to the clay, the liquid limit and plastic limit were 76 and 38, and with 6% cement these were 71 and 45, respectively. As shown in Fig. 4, the plasticity index of clay increased with cement and bentonite additives.

Clay-sand mixture

Clay-sand mixtures were initially characterized based on the liquid limit, plastic limit and plasticity index of clay-sand mixtures. The 60/40 and 30/70 (clay/sand ratio by weight) clay-sand mixtures were classified as CL (sandy clay) and SC (clayey sand) respectively according to USCS. As shown in Fig. 4, 8% sodium silicate solution increased the liquid limit and plasticity index of clay-sand mixtures. However, pure methanol destroyed the plasticity of clay-sand mixtures. With the addition of 6% bentonite, the liquid limit, plastic limit and plasticity index were increased for the clay-sand mixes. In fact, this small amount of additive sufficiently brought the liquid limit of both clay-sand mixtures (60/40 and 30/70) to over 45, which is also a criterion used in evaluating their suitability for soil liners [24]. Both bentonite (6% by weight) and sodium silicate (8% solution) increased the plasticity index of kaolinite clay–sand (30/70) mixture.

Consolidation

The long-term functional integrity of soil liners is affected by excess and differential settlement. The objective of the consolidation test is to simulate the compression of the soil under given external loads and to study the settlement behavior of soil over time. The effect of methanol on the compressibility of clay and clay–sand mixture was investigated under one-dimensional consolidation (ASTM D 2435). A fixed ring consolidometer was used, and the test samples were obtained from the compaction mold by pushing the ring into the compacted soil. The samples were saturated for two days, and the swelling was closely monitored before loading up to 3.2 MPa in four steps (50, 200, 800 and 3200 kPa) and unloaded. As recommended by the testing standard, loading was sustained for 24 hours at each step of loading. Representative consolidation curves, void ratio versus log-pressure, are shown in Fig. 5 for clay and clay–sand (30/70) mixture with water and methanol as pore fluids. The consolidation parameters, such as the compression index (C'_c) and the coefficient of

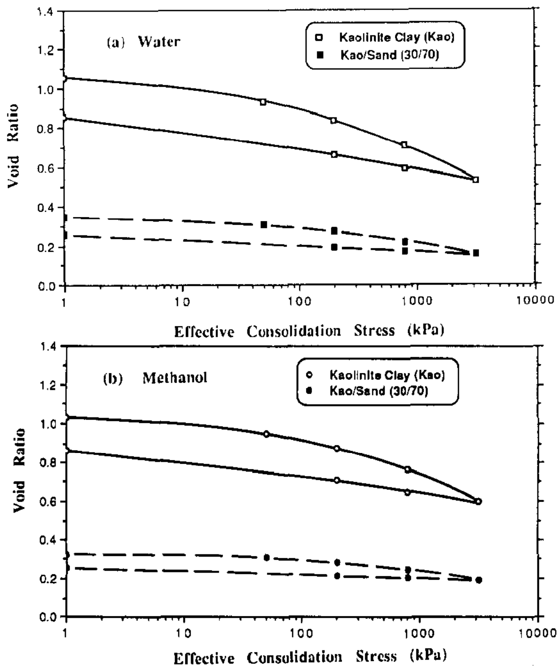

Fig. 5. Consolidation relationships for clay and clay–sand (30/70) mixture with (a) water and (b) methanol.

TABLE 1

Consolidation parameters for kaolinite clay and clay-sand mixture

Parameter	Kaolinite clay		Clay-sand (30/70) mix	
	Water	Methanol	Water	Methanol
Compression index (C_c')	0.30	0.27	0.10	0.09
Coefficient of consolidation (C_v cm^2/min)	0.047-0.14	0.040-0.135	0.066-0.55	0.065-0.42
Hydraulic conductivity (K, 10^{-8} cm/s)	1-5	0.9-2	2-4	1-3

consolidation (C_v), are summarized in Table 1. Calculating the consolidation parameters from load-settlement relationships (Casagrande logarithmic method) is described in any standard geotechnical engineering textbook [29]. Using C_v, the hydraulic conductivity of soils was determined indirectly [29] and is also summarized in Table 1. Notable changes in the consolidation properties were not observed because of the presence of pure methanol.

Hydraulic conductivity

Rigid-wall permeameters were used for the hydraulic conductivity study. The permeameter was designed with a double-ring base to separate flow that might occur near the sidewall from flow occurring through the central portion of the soil specimen. A schematic diagram of a double-ring rigid-wall permeameter is shown in Fig. 6a. The circular ring had a sharp edge and protruded into the soil a short distance (about 1 mm) to ensure separation of the flow that occurs through the central portion of the soil specimen (inner flow) from the outflow that may be affected by the sidewall leakage (outer flow). Since the inner ring area was equal to the outer ring area, if there was significant sidewall leakage, the outer flow was larger than the inner flow, and if the difference was greater than 15% the tests were terminated. Researchers have used a range of hydraulic gradients varying between 25 and 831 to perform the laboratory tests on natural and manufactured soils [5,6,13,14,17,18,25]. It is interesting to note that the hydraulic gradient normally encountered in the disposal sites is typically less than 20 [9]. Although it is necessary to conduct the tests with elevated hydraulic gradients to reduce testing time, soil piping or particle migration may occur and can significantly influence the measurement of hydraulic conductivity if the gradients are excessive. In this investigation, all the hydraulic conductivity tests were performed at room temperature (25°C, 77°F) under a hydraulic gradient of 100, reducing the testing times to a practical duration. Because the change in hydraulic head the level of permeant in the accumulator was so small (less than 1%), during permeation they were

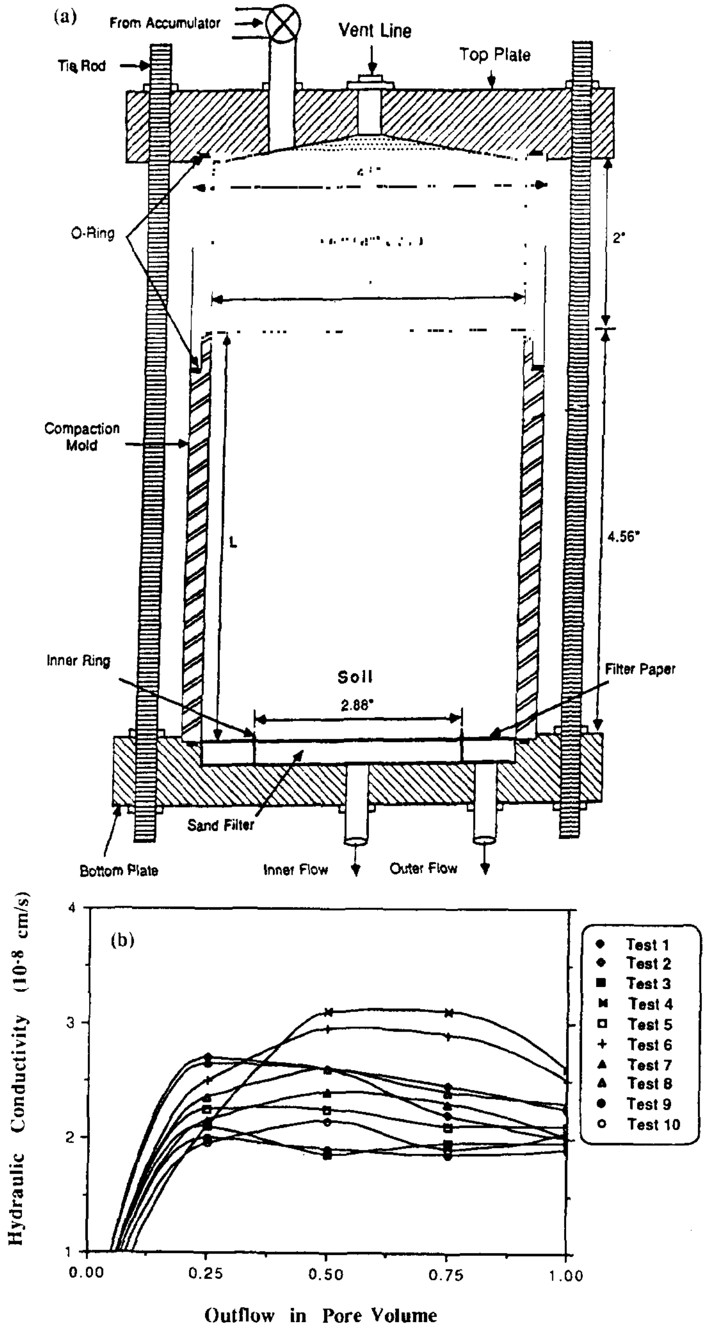

Fig. 6. Hydraulic conductivity test. (a) Schematic diagram for the rigid wall permeameter. (b) Reproducibility of hydraulic conductivity of kaolinite clay.

treated as constant-head tests. The hydraulic conductivity was calculated for each time interval as follows;

$$k=\frac{\Delta Q}{ia\Delta t},\tag{1}$$

where k is the hydraulic conductivity [L/T], (cm/s), ΔQ is the volume of permeant liquid [L^3], (cm^3) that flowed between two successive measurements in time Δt [T], (s), i is the hydraulic gradient (dimensionless), and a is the cross-sectional area of the soil specimen perpendicular to the direction of flow [L^2], (cm^2).

The reproducibility of the hydraulic conductivity measurements of kaolinite clay using the rigid wall permeameters is shown in Fig. 6b. Also, the quantity of permeants passing through the soil is represented in terms of soil pore volume (PV). The pH of the effluent solution was also measured at various time intervals.

Clay

The effect of (a) compaction water content and (b) type of permeant on the hydraulic conductivity of clay is shown in Fig. 7. The variation of normalized

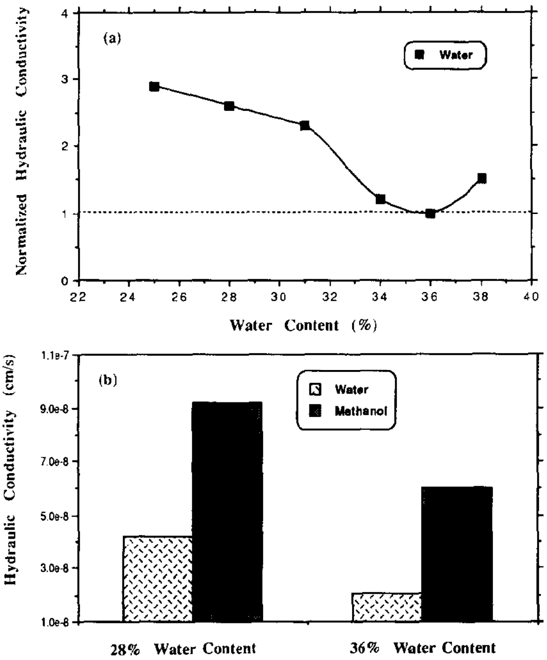

Fig. 7. Variation in hydraulic conductivity with compaction moisture content. (a) Water permeation. (b) Methanol permeation.

hydraulic conductivity (normalized with respect to minimum hydraulic conductivity of clay at 36% water content) with compaction water content is shown in Fig. 7a. Kaolinite clay compacted dry of optimum (25% water content) had a hydraulic conductivity which was three times greater than the clay compacted 2% wet of optimum (36% water content). Also, kaolinite clay was more permeable to methanol (> 2 times) than to water at different compaction water contents, as shown in Fig. 7b. The hydraulic conductivity of clay with water corresponds closely to the test results from the consolidation test.

Clay-sand mixture

Clay-sand mixtures were compacted at optimum water content for the hydraulic conductivity tests, using water and methanol as permeants. The variation in hydraulic conductivity with 70% sand content is shown in Fig. 8, which were in excess of the U.S. EPA limit. Also, the hydraulic conductivity for clay and the clay-sand mixtures have been related to the plasticity index in Fig. 9. The relationship between the hydraulic conductivity and the plasticity index for the soils under investigation may suggest that, by increasing the plasticity

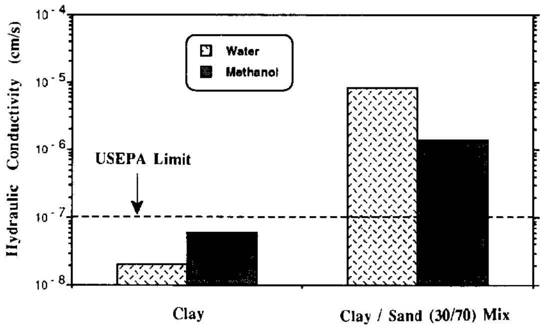

Fig. 8. Comparison of hydraulic conductivity of clay and clay-sand mixture (compacted at optimum moisture content) with water and methanol permeation.

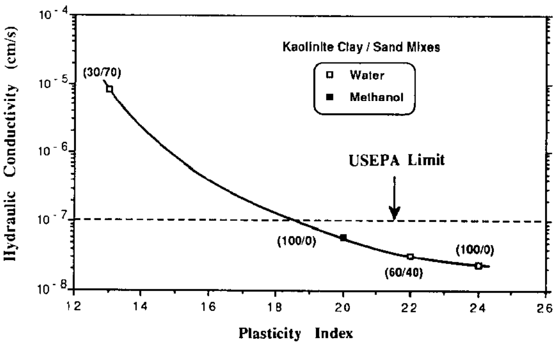

Fig. 9. Variation of hydraulic conductivity with plasticity index for clay and clay-sand mixture.

index of the soil with grout and additives, hydraulic conductivity could be lowered. Also, note that the hydraulic conductivity determined from the consolidation test underestimates the hydraulic conductivity measured using a rigid wall permeameter.

Seepage control

The effect of various additives on the hydraulic conductivity of kaolinite clays and clay–sand (30/70) mixture was investigated, using water as the permeant. The selected additives included bentonite (6%), cement (6%), and bentonite (3%)-cement (3%) mix. A comparison of the hydraulic conductivity of kaolinite clay with additives is shown in Fig. 10. It was observed that kaolinite clay with cement (6%) (dry by weight) yielded the lowest hydraulic conductivity than any other combination investigated. The pH of the outflow was 12.3 because of the high alkalinity of cement. The cement–bentonite (3% each) mix also lowered the hydraulic conductivity of kaolinite clay. The bentonite (6%) was capable of reducing the hydraulic conductivity of clay–sand mixture (about 10^{-5} cm/s) to lower than the U.S. EPA limit, and the pH of the effluent was 8.7. The addition of 6% of bentonite modified a CS soil (30/70 mix) to a CH soil, hence decreasing its hydraulic conductivity.

Suspension grouts such as bentonite (0.1% and 0.3%) and Portland cement (0.05% and 0.3%), and a solution grout (8% sodium silicate solution) were used to control the hydraulic conductivity of the clay–sand (30/70) mixture.

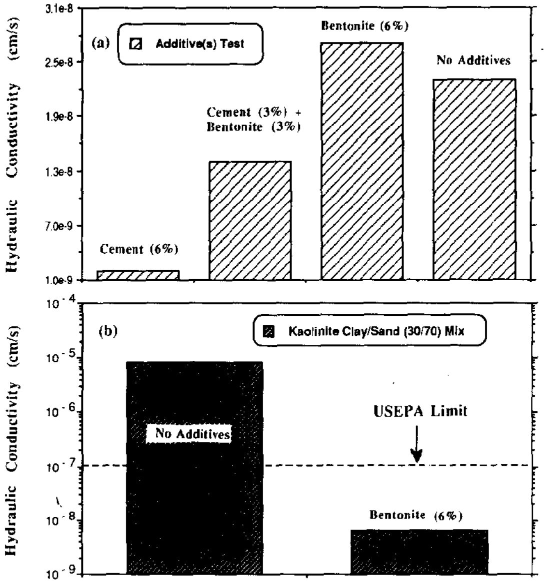

Fig. 10. Effect of additives on the hydraulic conductivity. (a) Clay. (b) Clay–sand mixture.

The hydraulic conductivity–time history for clay–sand mix during treatment is shown in Figs. 11 to 14. When sodium silicate (8% solution) grout was permeated through the clay–sand (30/70) mixture, the hydraulic conductivity was reduced to the U.S. EPA limit in a time period of 15 h (Fig. 11a), and the pH of the outflows increased from 7.3 to 11.2, as shown in Fig. 11b (pH–time history). Lowering the hydraulic conductivity with 8% sodium silicate solution

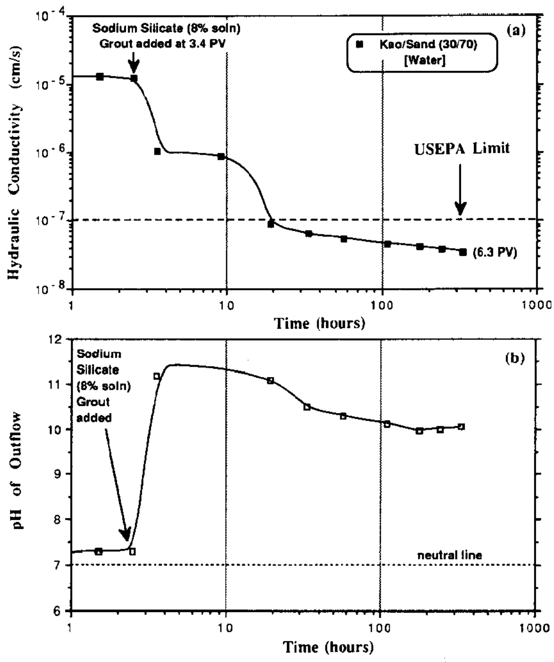

Fig. 11. Treatment with sodium silicate grout. (a) Hydraulic conductivity–time relationship. (b) pH–Time relationship for outflow.

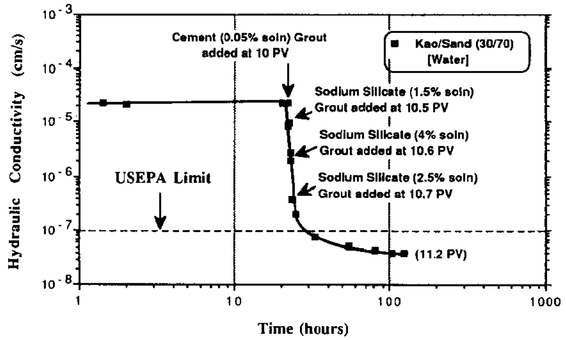

Fig. 12. Hydraulic conductivity–time relationship for clay–sand mixture treated with 0.05% cement grout and sodium silicate grout introduced at various concentrations.

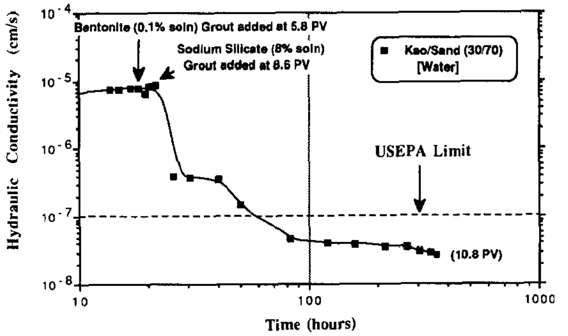

Fig. 13. Hydraulic conductivity-time relationship for clay-sand mixture treated with 0.1% bentonite grout and 8% sodium silicate grout.

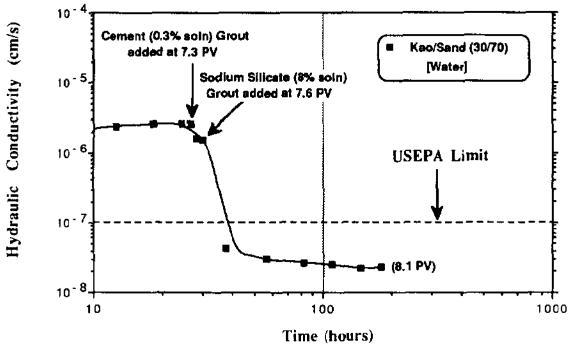

Fig. 14. Hydraulic conductivity-time relationship for clay-sand (30/70) mixture treated with 0.3% cement grout and 8% sodium silicate grout.

appeared to correlate closely with the changes in index limits (Fig. 2), which showed an increase in soil plasticity index. When very dilute cement (0.05% solution) grout was permeated, as shown in Fig. 12, the hydraulic conductivity decreased from 2.2×10^{-5} to 9.3×10^{-6} cm/s. A 1.5% solution of sodium silicate grout was then introduced; it lowered the hydraulic conductivity to only 1.9×10^{-6} cm/s. The addition of further 4% silicate grout appeared to reduce the hydraulic conductivity to 3.7×10^{-7} cm/s. As shown in Fig. 12, when an additional 2.5% silicate grout was used, the hydraulic conductivity decreased rapidly (total of 8 h) to satisfy the U.S. EPA's maximum limit for hydraulic conductivity (10^{-7} cm/s). The hydraulic conductivity was reduced to a value of 3.8×10^{-8} cm/s, and the pH of the final outflow was 9.8.

When bentonite (0.1% solution) grout was permeated to control the hydraulic conductivity of the clay-sand (30/70) mixture, there was only a slight change in hydraulic conductivity. However, when 8% solution of sodium silicate grout was added, the hydraulic conductivity was reduced to far below the U.S. EPA's limit in a period of 38 h, as shown in Fig. 13. The pH of the outflow after treatment was 9.5. When cement (0.3% solution) grout was used for treating the 30/70 clay–sand mixture, the hydraulic conductivity reduced slightly, but the pH increased from 7.8 to 8.9. When sodium silicate (8% solution) grout was added, the pH dropped sharply to 8.2 and further decreased to 8.0 as the test progressed. During this time period, the hydraulic conductivity was reduced to far below the U.S. EPA's limit, as shown in Fig. 14. When a mix of 0.3% of bentonite and cement grout was used, only a slight change in the hydraulic conductivity was observed until the 8% solution of sodium silicate was introduced, as shown in Fig. 15. The pH of the outflow after treatment was 9.3. All tests confirm the fact that 8% sodium silicate grout is effective in controlling the seepage in clay–sand (30/70) mixture.

Soils were contaminated by permeating at least one pore volume of methanol before treating them with grout solutions. Kaolinite clay compacted at 28% water content was contaminated and treated with a cement grout (0.1% solution) to reducing the hydraulic conductivity and the treatment time history is shown in Fig. 16. The hydraulic conductivity was reduced by 50% by this treat-

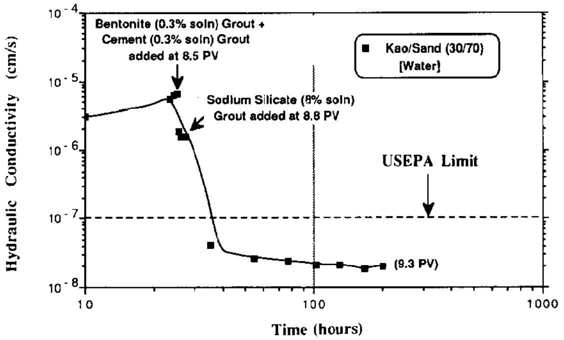

Fig. 15. Hydraulic conductivity–time relationship for clay–sand (30/70) mixture treated with 0.3% of each cement and bentonite grouts followed by 8% sodium silicate grout.

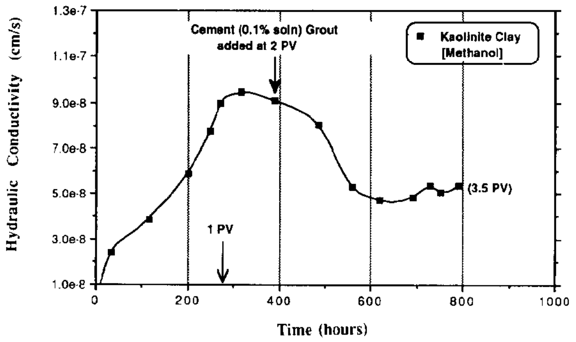

Fig. 16. Hydraulic conductivity–time relationship for methanol contaminated kaolinite clay (compacted at 28% moisture content) and treated with 0.1% cement grout.

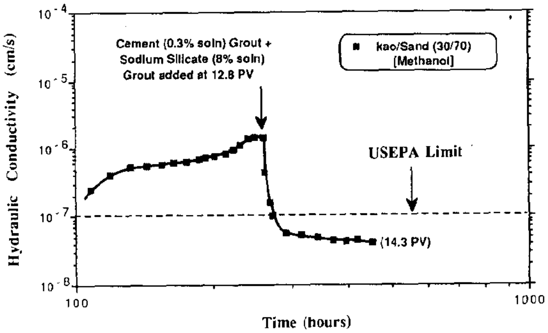

Fig. 17. Hydraulic conductivity-time relationship for methanol contaminated clay-sand mixture treated with a mix of 0.3% cement grout and 8% sodium silicate grout.

ment. Figure 17 shows the hydraulic conductivity-time history for the 30/70 clay-sand mixture initially permeated with about 12 pore volumes of methanol and treated with a mix of cement (0.3%) and sodium silicate (8%) grout. The hydraulic conductivity, which was 1.4×10^{-6} cm/s, was reduced to below 10^{-7} cm/s in a time period of 11 h, and the pH of the final outflow was 11.4

Conclusions

The behavior of kaolinite clay and clay-sand mixture in the presence of water and methanol was studied. Also, treatment to reduce seepage in permeable clays (clay-sand mixture), in order to satisfy the U.S. EPA maximum limit on hydraulic conductivity of 10^{-7} cm/s, using various dilute grouts and additives, has been investigated. Based on the extensive laboratory study, the following can be concluded:

(1) Adding sand to clay resulted in higher hydraulic conductivity and maximum dry unit weight with reduction in optimum moisture content and consolidation parameters. Pure methanol affected the hydraulic conductivity of clay and clay-sand mixture without affecting their consolidation properties.

(2) Using additives such as cement and bentonite (6% by weight) to the kaolinite clay and clay-sand mixture resulted in an increase in optimum water content. Cement and bentonite additives (6% by weight) are effective in reducing the hydraulic conductivity of clay and clay-sand (30/70) mixture, respectively.

(3) Sodium silicate (8% solution) grout can be used to reduce the hydraulic conductivity of the permeable kaolinite clays (hydraulic conductivity $>10^{-5}$ cm/s), contaminated with and without methanol, to below the U.S. EPA limit on hydraulic conductivity of 10^{-7} cm/s. Using a small quantity of cement and bentonite with the sodium silicate grout helps to lower the pH of the outflow.

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