Urethane grout for formation of waste barriers in sand

L'injection d'uréthane pour la formation dans le sable de barrières aux polluants

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SYNOPSIS: Injectability, reduction in hydraulic conductivity, and the dimensional characteristics of a waste barrier formed using urethane grout in sand were investigated. Results indicated that the performance of the urethane barrier was affected by acid and base chemicals. The hydraulic conductivity (k) of the grouted sand using deionized water was measured to be on the order of $5x10^{-8}$ cm/s. In comparison, a k value in the range of $1x10^{-4}$ cm/s to $1x10^{-6}$ cm/s was measured acid and base solutions were used.

1 INTRODUCTION

Confinement and containment technologies are needed to retard, or even prevent, the advancement of the contamination plumes into the environment until treatment efforts are implemented and completed. A wide variations in soil type, geological formation, and hydrogeologic conditions necessitates the investigation of various confinement technologies. One of the promising technologies is the use of permeation grouting to form blanket and curtain barriers or to form grout cones for encapsulation of areas of isolated concern. In a laboratory study conducted by Sherer (1986), sand was grouted with various chemical grouts at pressures of approximately 69 kPa. A field demonstration of permeation grouting was conducted by Moridis et al. (1995) at a gravel quarry in California with the purpose of investigating the feasibility of using permeation grouting in developing horizontal bottom barriers. Vertical injection wells were drilled into the subsurface and the grout was injected. After gelling, the grouted area was excavated in order to study the bulb characteristics. The grouts in this case satisfactorily gelled/crosslinked in the subsurface and fairly uniform bulbs were created despite the extreme soil heterogeneity. Laboratory permeability testing of the lab-grouted material was conducted. These results indicated a lower permeability than the field grouted soils. However, after multiple injections, the measured field permeability values were closer to the laboratory results.

The potential formation of an in-situ barrier using urethane/polyurethane as a permeation grout was investigated in this paper. A laboratory-scale testing program using uniformly graded Ottawa sand was conducted to investigate the viscosity, injectability, and the hydraulic conductivity performance of the formed barrier under acid and base solutions. Results are presented and discussed.

2 URETHANE GROUTS

Urethane grouts are hydrophilic resin solutions that react to produce a time-dependent hardening gel that fills the pore space of the soil matrix. Because urethanes are water reactive, they can change from a free-flowing liquid to an "impermeable" solid that bonds extremely well to wet surfaces.

Polyurethanes are formed by a chemical reaction between two components: an isocyanate and a polyol resin. The polyol component carries additives which determine the final cure characteristics of the grout (Micon 1994). Urethanes are designed to be mixed with water to initiate the formation of a flexible end-product. As reported by Sherer (1986) and Malone et al (1985), urethane has a moderate viscosity (20-60 cP), a formulation pH of 6.8-7.5, and a tensile strength of 137- 207 kPa. It is prone to shrinkage in unsaturated and dehydrating conditions; however, with the addition of moisture, 100% recovery can be expected. Urethane grouts can be injected as either a foam or a gel. In some instances, it may be appropriate to utilize a combination of foam and gel to develop a seal as in the case of a fractured rock terrain.

An important factor for the proper functioning of a grout barrier is its ability to maintain a low permeability under harsh environmental conditions. The chemical resistance of urethane grout and many others is documented in past studies by Sherer (1986), Bodocsi et al (1988,1991) and Carson (1988). Urethane compounds were found to perform extremely well in the presence of 100% acetone, reagent grade aniline, 100% ethylene glycol, reagent grade xylene, and 1 N hydrochloric acid (N=normality which is the number of gram-equivalent weights of solute per 1 L of solution). Carson observed unreliable and variable results with exposure to 100% methanol. Detrimental affects were observed when the urethane was exposed to cupric sulfate, 4 N hydrochloric acid, and 10% and 25% sodium hydroxide. Additionally, Sherer reported no variance in permeability due to a two fold increase in net confining pressure for a selected number of urethane grouts.

3 MATERIALS AND METHODS

Work in this study was conducted using an air dried, uniformly graded Ottawa sand as the media to be grouted and polyurethane gel as the grout material. Laboratory testing in accordance with ASTM Standards was conducted to determine the physical characteristics of the Ottawa sand. These tests included: moisture content (ASTM D 2216), specific gravity (ASTM D 1429), minimum and maximum densities (ASTM D 4254 83 and D 4253 83). Table 1 includes a summary of the measured sand properties and Figure 1 shows the particle size distribution for the test sand The hydraulic conductivity of the sand was determined using a rigid wall permeameter in accordance with ASTM Draft Standard Method for Measurement of Hydraulic Conductivity Using a Rigid Wall, Compaction-Mold Permeameter.

Table 1: Summary of 20/30 Ottawa Sand Properties

Soil Property	Value
Moisture Content	.04%
Specific Gravity	2.65
(γ_{min})	1.52 g/cm^3
(γ_{max})	1.76 g/cm^3
k	2 x10^{-3} cm/s

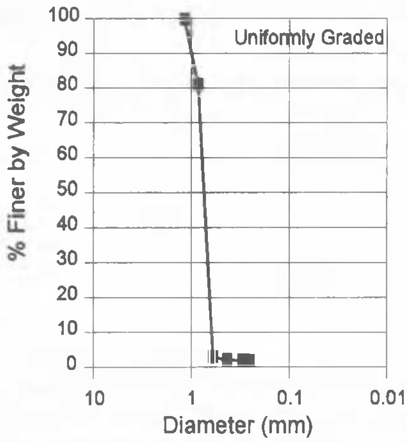

Figure 1. Grain Size Distribution of the Sand

3.1 Study Grout

The urethane grout was supplied by the 3M Company under the trade name Scotch-Seal (TM) Brand Chemical Grout 5610 (Gel). After reviewing the product literature and past studies with similar materials (Carson 1988, Sherer 1986), it was concluded that the material may have the potential to serve as a subsurface barrier to plume transport. The 5610 gel is a hydrophilic material most commonly used for sewer and water line rehabilitation projects (i.e., sealing to prevent infiltration and exfiltration problems in sewage systems.)

The urethane grout used in this research was comprised of five main ingredients: a urethane prepolymer, acetone, toluene 2,4 - diisocyanate (2,4 TDI), toluene 2,6 - diisocyanate (2,6 TDI), and benzoyl chloride. The latter four compounds are subject to reporting requirements of the Emergency Planning and Community Right-to-Know Act (EPCRA) of 1986 and 40 CFR 372. However, the stabilized grout material is supplied by 3M in premixed containers.

Water (pH between 5 and 9) alone can be used as the activator, however, there are additives available to customize the grout formulation for a specific need. A water to grout ratio of 5:1 to 12:1 is utilized with the 5610 gel. For soil stabilization, an 8:1 ratio is suggested as the lowest ratio and higher ratio formulations are recommended. Additives to the urethane grout include :

1. Gel time extender (GTE) which extends the time period before gelation of the grout occurs. The material is relatively inert and is comprised entirely of water and sodium lauryl sulfate.

2. Accelerator additive to decrease the gelation time and is comprised of N,N-Dimethyl ethanolamine.

3. Gel reinforcing (GR) agent to increase the strength of the Chemical Grout 5610 and reduce the possibility for gel shrinkage under dry conditions. Additionally, it is used to increase the grouts resistance to freeze/thaw cycling, chemical and biological degradation, and soil movement.

Based on several factors related to gel time, initial viscosity, and materials cost, a 10:1 mix ratio was selected for this study. Two 10:1 mixes were studied with the first mix (Mix 1) having the activator solution comprised of 60% water, 30% gel time extender and 10% gel reinforcer. In comparison, the activator solution for the second mix (Mix 2) was 100% gel time extender.

The grout viscosity was measured using viscosity tests in accordance with ASTM D 4016-93 *Standard Test Method For Viscosity of Chemical Grouts by Brookfield Viscometer*. A Model

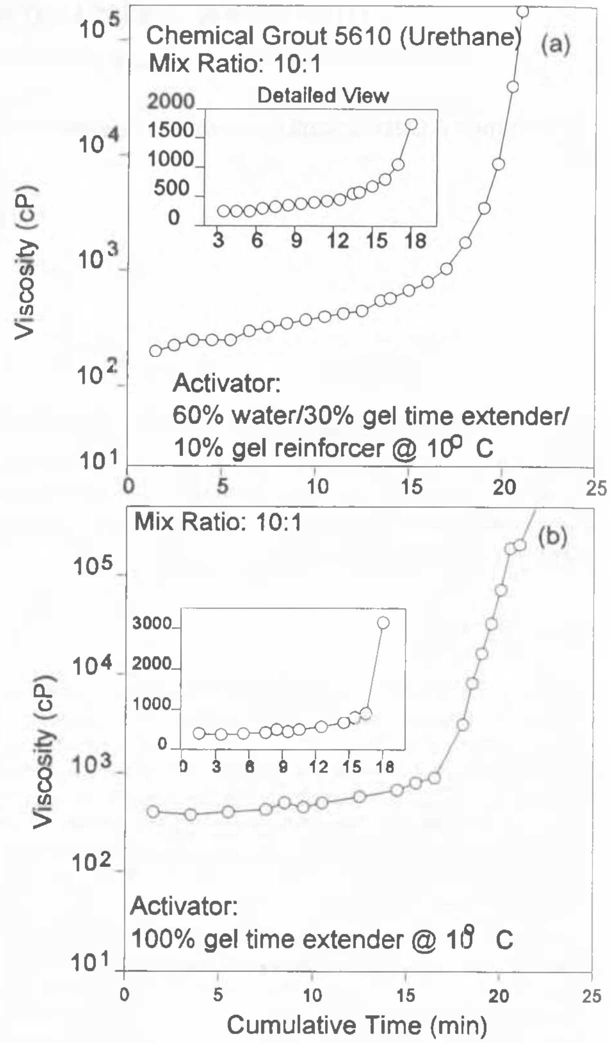

Figure 2. Variation of Viscosity with time: a) Mix 1 and b) Mix 2

LVT #4 spindle was utilized for all the viscosity tests which were conducted on 400 mL samples.

Using 100% water as activator with a mix ratio (water:gel) of 10:1 yielded a short gel time of 2.5 minutes. The addition of gel time extender (GTE) along with chilling the activator as recommended by Bodocsi (1991) resulted in extending the gel time to 18 minutes as shown in Figure 2 (a,b). Results indicated that test Mix 1 has an initial viscosity of 200 cP with gelation time of approximately 21 minutes. As the percent of the GTE was increased from 30% to 100%, the initial viscosity was increasedfrom 200 cP to 400 cP with no apparent increase in the gelation time.

4 COLUMN TESTING

Test columns 305 mm in diameter were used to investigate the injectability of the urethane into the test soil as well testing the feasibility of forming a barrier. Figure 3 shows a schematic diagram of one of these columns. The columns were constructed of clear acrylic tubing (6.4 mm wall thickness) with 355.6 mmx355.6 mm acrylic top and bottom square plates. The columns are 607 mm in height. Prior to filling the column with sand, geosynthetics (geonet and geotextiles) were placed over the bottom plate. These materials served as a filter and allowed for the permeant to reach the drainage port with no piping of particles.

The grout injection probe was positioned inside the column before commencing with filling activities. It was suspended in the

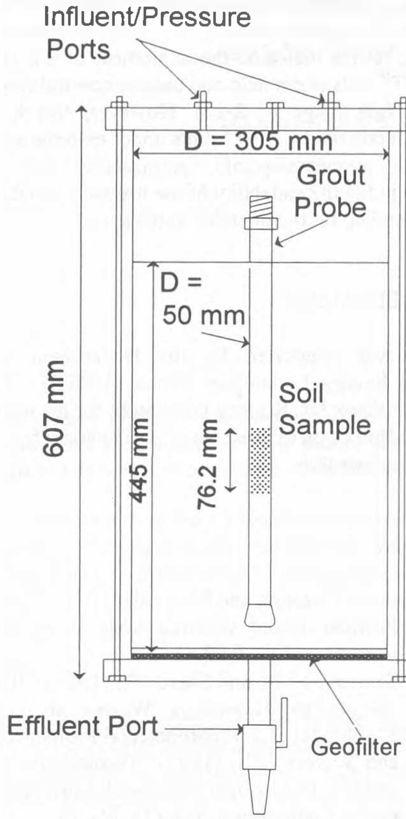

Figure 3. Diagram of the Test Column

center of the column approximately 25.4 mm from the bottom plate and was held in position through the use of laboratory ring stands. To achieve minimum unit weight samples, the sand was placed in the column using a small pouring container while consistently maintaining the drop height of the sand at a minimum. To achieve maximum unit weight samples, the sand was placed in 100 mm layers and a 290 mm circular plate, outfitted with vibrators, was used for compacting each layer for 5 minutes. Specimens prepared through these procedures were consistently within 5% of the unit weight values presented in Table 1.

4.1 Grout Injectability

Grout injection was accomplished by the use of a peristaltic pump with dual drive heads. The dual heads enabled the pump to also be used for in-line mixing of the grout and the activator components at preset ratios. Static mixers were placed in the injection probe as additional assurance that the grout components were thoroughly mixed prior to injection. Eleven (11) injectability tests were conducted to study the effect of varying porosity, the dimensions of the injection probe and the column surcharge on the formed grout bulb.

Approximately, 5.5 liters of the grout solution was prepared and injected into each column. The flow rate was set to 4 L/min for all of the injectability tests. However, and as an additional measure, the total time of injection was recorded to ensure that the flow rate was constant. The grouted specimens were permitted to cure for 24 hours after which they were extruded for bulb characterization.

The injection pressures and the time when the grout was first observed at the columns boundary were monitored. Both the pump flow rate and injection volume (5.5L) were held constant throughout these experiments. Table 2 shows the grout bulb characteristic dimensions and the measured injection pressures as a function of the dimensions of the injections probes. For all the tests performed using the 6.9 kPa surcharge, the injection pressure

Table 2. Injectability Testing Results

No.	n [1]	P.L. [2] cm	P.S. [3] mm	q [4] kPa	L/D	Injec. Press. (kPa)	Ave. Band Width
1	0.42	3.81	1.6	6.9	1.11	206.8	11.9 cm
2	0.36	3.81	1.6	6.9	1.15	137.9	16.2
3	0.34	3.81	1.6	6.9	1.10	206.8	16.0
4	0.42	7.62	1.6	6.9	1.33	206.8	10.6
5	0.36	7.62	1.6	6.9	1.13	206.8	13.3
6	0.34	7.62	1.6	6.9	1.19	206.8	22.1
7	0.41	15.24	1.6	6.9	1.46	137.9	12.3
8	0.36	15.24	1.6	6.9	1.29	165.5	14.8
9	0.34	15.24	1.6	6.9	1.29	186.2	15.8
10	0.43	3.81	1.6	13.	1.09	206.8	13.4
11	0.43	3.81	3.2	6.9	1.07	275.8	16.0

1= n denotes porosity, 2= P.L. denotes perforation length, 3=P.S. denotes perforation size, 4= q denotes column surcharge

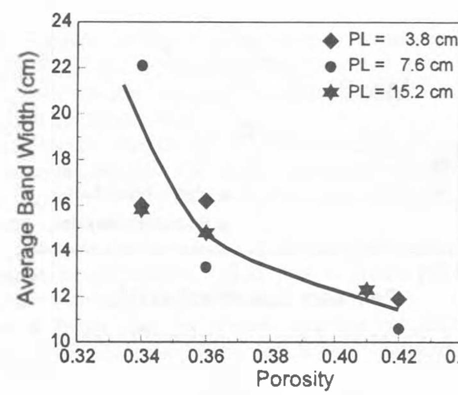

Figure 4. Variation of the Average Bulb Thickness with Soil Porosity

varied from 137.9 - 206.8 kPa. Lower grout injection pressures may be attributable to the increase in the surface area utilized for injection as they were mainly observed for the probes with the 15.2 cm perforation length.

Average band width (i.e., barrier thickness) measurements were recorded after the completion of the column grouting. Based on the limited data of this study it appears that the band thickness is inversely proportional to the porosity as illustrated in Figure 4. The average band width decreased from approximately 220mm for n=0.34 to 120 mm for n=0.42. No trend was observed in the observed in the injection pressure while varying the porosity in each test set. It was observed that a larger penetration radius with a decreased time for completing the injection was obtained for the smaller perforation size. Tests 10 and 11 (refer to Table 2) were conducted to determine the effect of varying the surcharge and the perforation size, respectively. There was no apparent effect of increasing the surcharge to 13.8 kPa. However, by changing the perforation size (comparing Test 1 with Test 11), the injection pressure was 69 kPa higher than for the larger perforation size.

5 HYDRAULIC CONDUCTIVITY

Samples were collected from the grout bulbs using a 71 mm diameter shelby tube and then subjected to permeability testing in accordance with ASTM D 5084. Samples heights typically ranged

Table 3. Solutions Used For Hydraulic Conductivity Determination

Solution	Concen tration	pH
Hydrochloric Acid (HCl)	0.01 M	2.0
	0.1 M	1.0
	1.0 M	.01
Sodium Hydroxide	0.01 M	12.0
	0.1 M	12.8
	1.0 M	13.3

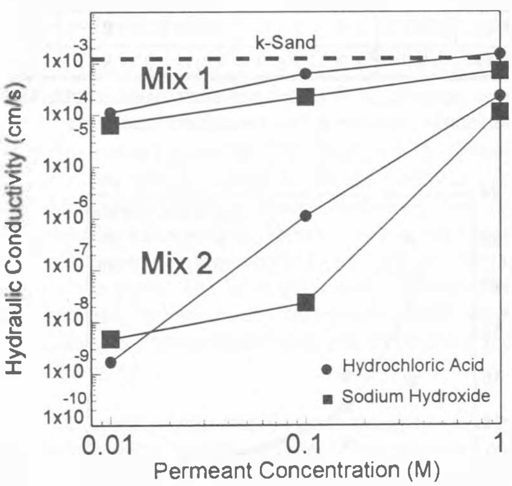

Figure 5. Variation of k as a Function of Leachate Concentration

from 3 cm to 8 cm. To reduce the likelihood of diffusion through the flexible membrane, the samples were wrapped with a thin film of Teflon® tape as suggested by Daniel and Trautwein (1994). Permeation was conducted with acid and base solutions as presented in Table 3. A reference k value of 2×10^{-3} cm/s was measured for the ungrouted sand.

Figure 6 summarizes the results of the hydraulic conductivity experiments. A k value on the order of 1×10^{-4} cm/s was measured using 0.01 M permeant (pH of 2.0) for Mix 1 containing 60% water. This value is one order of magnitude less than the k of the ungrouted sand. However, as the permeant concentration was increased to 1.0 (pH value was reduced to 0.01) the measured k value was comparable to that obtained for the ungrouted sand. In case of Mix 2 with 100% GTE the k value was measured to be on the order of 1×10^{-9} cm/s under acid and base concentrations of 0.01 M and 0.1 M (pH range of 2-12) but was dramatically increased to 1×10^{-4} cm/s under the extreme acid and base solutions prepared using 1M Hydrochloric Acid (HCl) and 1M Sodium Hydroxide (NaOH), respectively. Accordingly, a permeant-specific permeability test should be conducted to judge the suitability of the urethane grout as a barrier material depending on the intended application.

6 SUMMARY AND CONCLUSIONS

A laboratory-scale testing program was conducted to investigate the viscosity, injectability, and the hydraulic conductivity performance of barrier material formed using polyurethane. Using a mix ratio of 1:10 with the activator being 100% GTE, results indicated the attainment of a k value on the order of 1×10^{-9} cm/s under acid and base concentrations of 0.01 M and 0.1 M (pH range of 2-12). However, this k value was dramatically increased to 1×10^{-4} cm/s under extreme acid and base solutions. A permeant-specific permeability test should be conducted to judge the suitability of the urethane grout as a barrier material depending on the intended application.

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