Organophilic Bentonites for Composite Liner Systems

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Abstract

For use as a component in liner systems of waste deposits, organophilic bentonites with a broad adsorption ability are needed, since the composition and concentration of leakage water varies with time. As a result, the adsorption of different organic compounds in varying concentrations is quantitatively determined and compared using percolation columns for several organophilic bentonites. The data indicated that a best suited adsorbent can be determined for a given organic compound, an interesting aspect for cleaning of organically contaminated industrial waste waters. A silty sand is blended with three selected bentonites of various organophilicity to perform hydraulic conductivity tests and diffusion tests. A considerably increased contaminant retention time is observed. The shear strength and elasticity of soil samples improved with organobentonites are found to be unaffected compared to unimproved soil samples. As a result of this study, a practical application for organo bentonites is in the construction of waste deposit liners where an increased efficiency with respect to contaminant migration is provided.

Introduction

Argillaceous soils are used as mineral sealing layers in composite liner systems. Sodium- or calcium bentonites are added in appropriate percentages to minimize the hydraulic conductivity of the liner material. In addition, the ability of bentonites to adsorb pollutants results in an increased contaminant retention. However, natural clays and bentonites primarily adsorb only heavy metals and polar compounds in considerable amounts. The adsorption and retention of non-polar organic compounds and their retention in the barrier is low.

Official standards of different countries require permeabilities between 10^{-8} to 10^{-10} m/s and, therefore, only consider hydraulic contaminant transport through a clayey liner. In fact, diffusive contaminant transport may predominate over hydraulic transport due to the previously mentioned low permeabilities. GRAY & WEBER (1984) present a theoretical analysis

indicating that solutes are even able to diffuse against an hydraulic gradient. Diffusive transport mechanisms are generally ignored by the common methods defining the long term behavior and quality of sealing layers.

Organophilic bentonites are known to be good adsorbents for organic compounds. Various authors report on waste stabilization and contaminant retention by organophilic bentonites (ALTHER et al., 1988; 1986; SOUNDARARAJAN et al., 1990; STREET & WHITE, 1963a,b). In the presence of polar organic molecules, organophilic bentonites are also able to adsorb heavy metal ions (STOCKMEYER & KRUSE, 1991).

WEISS (1989) and ALTHER et al. (1989) suggest the use of organophilic bentonites in composite liner systems to increase the adsorption capacity of the mineral barrier for organic and inorganic pollutants. A maximum retention of contaminants is achieved if both hydaulic conductivity and diffusion are minimized together by an increased adsorption capacity of the liner material.

The intention of this paper is to investigate and compare the adsorption behavior of different organophilic bentonites. In addition, organophilic bentonites are blended with a fine-grained soil which has been used for the construction of a sealing layer.

Diffusion and hydraulic contaminant transportation are studied on samples improved with hydrophilic and organophilic bentonites. The stability, compactivity and shear strength are also investigated for practical applications.

Materials

All bentonites used are commercially available products. They differ in the amount of original metal cations, the degree of exchange with organic counterions, and the kind of the organic cation.

Table 1: Organophilic bentonites. DMDO = dimethyl dioctadecyl ammonium, OBDM = octadecyl benzyl dimethyl ammonium, exchange = degree of inorganic cations replaced by the organic cations, preparation = way of preparing the organo bentonite from the rear material.

	Tixosorb	Tixosorb VZ	Tixogel VP	Tixogel VZ	Viscogel B4
org. Cation	DMDO	OBDM	DMDO	OBDM	DMDO
chain length	C-18	C-18	C-18	C-18	C-16/18
total CEC	80-100	80-100	80-100	80-100	80
exchange	50% of CEC	50% of CEC	100% of CEC	100% of CEC	100% of CEC
raw mat.	Ca-bent.	Ca-bent.	Na-bent.	Na-bent	Na-bent
preparation	dry	dry	wet	wet	wet

Montigel is a natural, unmodified Ca^{2+}-bentonite (MÜLLER-VONMOOS & KAHR, 1983). The "semiorganophilic" bentonite *Tixosorb* (Table 1) is manufactured from a Ca^{2+}-bentonite and is exchanged by approximately 50% of its cation exchange capacity (CEC) by dimethyl dioctadecyl ammonium ions (DMDO). The average alkyl chain length of the organic cation is C-18. The total CEC of the original Ca^{2+}-bentonite is 80 meq/100g. *Tixosorb-VZ* is similar to the Tixosorb and differs only in the type of the exchanged organic cation (octadecyl-benzyl-dimethyl ammonium, OBDM). In the "semiorganophilic" Tixosorbs organophilic surfaces and hydrophilic surfaces coexist. *Tixogel VP* and *Tixogel VZ* are prepared from a Wyoming Na^{+}-bentonite. Both Tixogels are exchanged with organic cations to about 100% of the CEC. Tixogel VP is exchanged with the DMDO cations, and Tixogel VZ with the OBDM cations. *Viscogel B4* is a product prepared from a blend of 50% Turkish Na-bentonite and 50% Wyoming Na-bentonite. The organic cation is also a DMDO. The degree of ion exchange is about 100% of the CEC. A more detailed description of the organophilic bentonite samples is given by STOCKMEYER (1991).

The organic compounds used in this study are *phenol, aniline, nitroethane, diethyl ketone, ethoxy acetic acid, maleic acid,* and *hexadecyl pyridinium bromide* of analytical grade. The compounds represent various groups of organical compounds which are found in leachates from waste deposits.

A silty sand (<2mm) was used as the base material for all tests with bentonite admixtures. The grain size distribution is displayed in Fig. 1. The non-plastic material consists of 70% sand, 25% silt and 5% clay fraction (illite and mixed layer illite/smectite)(by dry weight). The plasticity index of the base material was I_p=0.
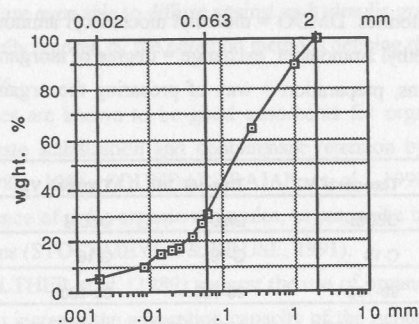
Fig. 1: Grain size distribution of the base-material.

Methods

The adsorption effectiveness of the organophilic bentonites was quantitatively determined by percolation tests (STOCKMEYER, 1991). Test solutions for each organic compound were prepared in concentrations (c_0) of 1 g/l and 10g/l. For the ethoxy acetic acid, concentrations of 10g/l and 20g/l were used in order to exceed the minimum detection limit for this compound using the HPLC analytical system. For the other compounds, the detection limits are below 0.01 g/l.

Amounts of 10g air-dried organophilic bentonite were filled into percolation columns with only slight compaction, and 80ml of the different test solutions were then added on top to percolate through the clay sample. Eluates were again filled into the percolation columns; no fresh test solution was added. Six of such percolation cycles were repeated over a time period of 6 weeks. Therefore, within the given boundary conditions (10g bentonite/80ml solution) an equilibrium state between adsorption and desorption will result for every percolation test (STOCKMEYER, 1991). The final concentrations (C_f) of the percolates were determined by HPLC and the amount of the compound adsorbed in the bentonite sample was calculated by

$$A = \frac{(C_0 - C_f) \cdot 100}{C_0} \, [\%]$$

A = adsorbed amount in percent of amount added
C_0 = concentration of the starting solution (g/l)
C_f = final concentration of the percolate (g/l)

It should be noted that the adsorbed quantities do not represent the maximum adsorption capacity of the organophilic bentonite. For example, a maximum adsorption capacity of 1100mg/10g of a DMDO bentonite was reported for phenol by STREET & WHITE (1963a), and of 2200 mg aniline per 10g of a octadecyl-trimethyl ammonium bentonite by STREET & WHITE (1963b). However, all results of this study were obtained within the same boundary conditions for all tests and can be used for comparison of the adsorption effectiveness of the different organophilic bentonites. Furthermore, in the opinion of the writer, it is not critically important to know the maximum adsorption capacities for single substances, because if mixtures of components of a real seepage water are to be adsorbed, competition reactions for adsorption sites in the clay will occur. The amount of an adsorbed component from a mixture can be far below the possible maximum adsorption from a pure solution. The adsorption selectivity of a clay for a specific component and the degree of desorption are more important than the maximum adsorption capacity.

For the hydraulic conductivity tests, samples of the base material were improved by admixing 5% of Montigel, Tixosorb and Tixogel VP. The consolidation and hydraulic conductivity of the test samples with water and the 10g/l phenol solutions were determined in oedometer cells (diameter 5.64cm, height 2cm, gradient i=50). All samples were prepared with a placement water content of approximately 20% and tests were performed in duplicate.

The load steps corresponded to applied vertical pressure of 4, 12.5, 25, 50, 100, 200, 400 and 800 kN/m^2. After consolidation of the first two load steps and drainage of water, the saturation of the samples was supposed to be Sr=1. Time-settlement curves were recorded for every load step, and hydraulic conductivity tests were performed for each load step.

During the first two load steps of all conductivity tests the samples were permeated with water. Then, water was replaced by the phenol solution of constant concentration (10g/l). The volume of the permeated solution was recorded and related to the pore volume. The phenol concentration in the effluent and the break-through of the initial phenol concentration was measured by HPLC (Fig. 3).

Diffusion was also measured on samples of the base material improved with 5% of the bentonites. The test solution was again 10g/l (10,000ppm) phenol in water. Standard Proctor density and corresponding optimum water content were determined separately for every sample, and the corresponding amounts of dry sample and water were mixed and filled into diffusion cells (Fig. 2). The material was then statically compacted to 50 cm^3 to attain maximum Proctor density.

The sample was then saturated with water pressed through the sample from bottom to top (inlet and drain open, outlet closed). To start diffusion, the drain was closed and the lower sinter disc rinsed with the phenol test solution to replace the water (inlet and outlet open). The drain was kept closed to perform transient diffusion experiments without any superposed

hydraulic flow (HASENPATT et al., 1989; MOTT et al., 1989). A concentration gradient was the only propelling force during diffusion. The diffusion front migrated through the sample. The experiments were stopped before the diffusion front reached the top of the sample to meet the conditions of transient diffusion (HASENPATT et al., 1989). The corresponding time periods were determined by separate test series.
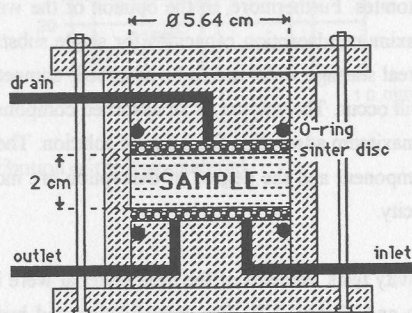

Fig. 2: Diffusion cell.

After the diffusion test period, the cylindric sample was removed from the diffusion cell and cut along its diameter into thin slices of approximately two millimeters thickness. Each slice was analyzed to determine the actual phenol distribution in the sample (Fig. 4). The diffusion coefficients were calculated by the method of KAHR et al. (1985) and HASENPATT et al. (1989). It is assumed that the adsorption of a diffusing compound is linearly correlated to the concentration of the adsorbate. The apparent coefficient of diffusion D is related to the coefficient D_e (no adsorption and retention) by a retention factor R:

$$(1) \qquad D = \frac{D_e}{R}$$

(CRANK, 1975, p.326; HASENPATT et al., 1989, p.187).

A possible analytical solution of Fick's second law for the diffusion is to assume a Gaussian distribution of the concentration in the sample (HASENPATT et al., 1989) which leads to:

$$(2) \qquad \log c = K * \frac{0.1086 * x^2}{D * t}$$

(HASENPATT et al., 1989, p.186)

with K = constant, c = concentration (mol/m^3) at time t (s) and distance from bottom of sample x (m). If the concentration distribution obtained from the sample slices is plotted as

log c versus the square of the distance (x^2), then the slope of the straight regression line is proportional to the apparent diffusion coefficient D (HASENPATT et al., 1989). The discrepancy between this simplified method and an exact mathematic solution is smaller than the precision of the measurement. In addition, the purpose of this study is to demonstrate the retarding effect of organoclay admixtures on diffusion.

Finally, the strength and elasticity were determined on samples of base-material improved with 5% of the bentonites to consider placement behavior and practical applicability. The samples were compacted to cylindric samples (standard Proctor) which were used for uniaxial unconfined compression tests.

Results and Discussion

The results of the adsorption measurements are shown in Table 2 for each organophilic bentonite.

Table 2: **A** = Amount adsorbed in percent of amount added. Bold numbers indicate initial concentrations C_0 of the test solutions (g/l).

		1 g/l	10 g/l			1 g/l	10 g/l
Phenol	Tixosorb	94.0	69.5	Diethyl	Tixosorb	48.0	37.3
	Tixosorb VZ	84.0	55.0	ketone	Tixosorb VZ	42.0	29.6
	Tixogel VP	96.0	93.2		Tixogel VP	90.0	42.8
	Tixogel VZ	97.0	91.9		Tixogel VZ	49.0	18.1
	Viscogel B4	95.0	88.3		Viscogel B4	93.0	43.1
Aniline	Tixosorb	98.0	71.0	Maleic	Tixosorb	44.0	19.0
	Tixosorb VZ	74.0	69.1	acid	Tixosorb VZ	40.0	16.0
	Tixogel VP	100.0	85.0		Tixogel VP	97.0	43.0
	Tixogel VZ	81.0	79.0		Tixogel VZ	94.0	55.0
	Viscogel B4	99.0	84.0		Viscogel B4	86.0	31.2
Nitro	Tixosorb	79.0	86.0	Hexadecyl	Tixosorb	41.0	45.7
ethane	Tixosorb VZ	63.0	75.0	pyridinium	Tixosorb VZ	45.0	53.8
	Tixogel VP	96.0	90.4	bromide	Tixogel VP	91.0	90.9
	Tixogel VZ	89.0	89.9		Tixogel VZ	93.0	93.1
	Viscogel B4	93.0	84.3		Viscogel B4	92.0	91.9

		10 g/l	20 g/l
Ethoxy	Tixosorb	13.7	22.4
acetic acid	Tixosorb VZ	35.8	18.9
	Tixogel VP	34.9	26.2
	Tixogel VZ	38.4	31.4
	Viscogel B4	20.0	30.7

Adsorption of even more than 90% (1 g/l solution) of phenol confirms that the bentonites examined in this study are good adsorbents for phenol. For the 10 g/l test solution, the adsorption (in % of amount added) was generally less effective. Besides Van der Waals interactions the hydroxy group of phenol makes hydrogen bonds to the hydrophilic clay mineral surface (COWAN & WHITE, 1962; STREET & WHITE, 1963a+b). SOUNDARARAJAN (1989) confirmed the existence of hydrogen bonding between the OH-group and surface oxygen of the bentonite. Van der Waals interactions seem to be the preferred adsorption mechanism at the phenol concentrations used in this study as the totally organophilic bentonites showed a higher adsorption than the partially organophilic bentonites. A distinct dependence of phenol adsorption to the kind of organic cation was not found.

The adsorption of the organoclays was also high for aniline. A generally more complete adsorption of the available aniline quantity was observed for lower concentrations of the test solutions. Tixosorb VZ and Tixogel VZ adsorbed smaller amounts of aniline from a 1 g/l solution. The DMDO cations seem to improve aniline adsorption in comparison with OBDM cations. Aniline is more polar (1.53 debeye) than phenol (1.45 debeye) and hydrogen bonding can also be supposed for aniline.

From the 1g/l solution both partially organophilic Tixosorbs showed a distinctively lower adsorption for nitroethane than the totally exchanged bentonites. It seems that the OBDM cations again reduce the adsorption. From the 10g/l solution all the amounts adsorbed were very close and the influence of the type and degree of exchange seems to be less distinct. Nitroethane can be adsorbed by hydrogen bonds to the clay mineral edges, directly or through a water bridge. The polarity of the molecule also allows dipole interactions, and the ethyle group may promote organophilic interactions with the organic cations.

A low adsorption of diethyl ketone was found for the organophilic bentonites. Only the totally organophilic DMDO bentonites Tixogel VP and Viscogel B4 reached higher percentages. The OBDM cation of the -VZ bentonites seems to be unfavorable for diethyl ketone adsorption. A generally lower adsorption was obtained for the 10g/l test solution. The ketone molecule can only accept hydrogen bonding from the hydroxy groups at the clay edges, and can be easily displaced by water. Van der Waals forces represent the main adsorption mechanism on the totally organophilic bentonites.

Generally, all examined organoclays attained a low adsorption of ethoxy acetic acid; the OBDM bentonites showed a higher adsorption. The partially organophilic products reached only slightly lower values than the totally exchanged bentonites. Ethoxy acetic acid is polar and easily soluble in water. Competitive reactions with water result in a low efficiency for hydrophilic adsorption.

The adsorption of maleic acid was also low. Organophilic interaction seems to be predominant for maleic acid as the adsorption of maleic acid approximately doubles at complete organophilic exchange of the bentonites. A decrease of the adsorption was observed at the higher

acid concentration. The relatively good adsorption performance of the OBDM modified bentonite is possibly due to an affinity between the benzyl group of the organic ion and the C=C double bond of the acid.

Hexadecyl pyridinium bromide is an organic salt, composed of the HDP^+ cation and the Br^- anion. Thus, for the only partially organophilic exchanged bentonites, further ion exchange between Ca^{2+} counterions and HDP^+ ions could be expected. On the totally organophilic exchanged bentonites the adsorption is more than 90% for both solution concentrations. Tixosorb and Tixosorb VZ reached lower adsorption levels. The HDP.Br adsorption by the totally exchanged bentonites is attributed to hydrophobic interactions. Ca^{2+} determination in the eluents indicated that not all HDP^+ ions did displace equivalent amounts of Ca^{2+} ions.

The organobentonites show considerable contaminant retention due to the high adsorption affinities for organic compounds. The break-through curves are displayed in Fig. 3. The break through of phenol was observed in the permeate of the unimproved base-material after permeation of approximately five pore volumes of the 10g/l (10,000ppm) phenol solution. The base-material improved with Montigel showed a somewhat increased phenol retention with the (C/C_0 = 1.0) break-through after approximately seven pore volume units.

Improvement with Tixosorb and Tixogel VP shifts the (C/C_0 = 1.0) break-through point to nearly ten pore volumes. This volume corresponded to approximately 150ml of a 10g/l phenol solution passing through a soil sample 2cm thick and with an area of 25cm^2 (void ratio e=0.47). The hydraulic transport of phenol is retarded until the adsorption capacity of the organobentonites is saturated.
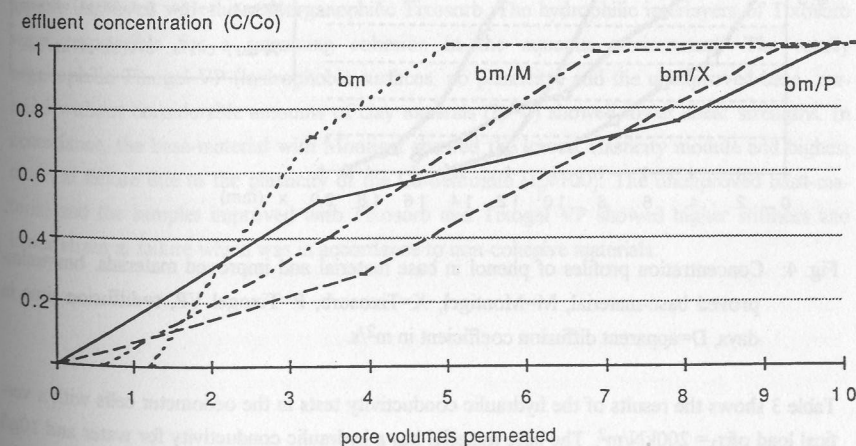

Fig. 3: Break-through curves for phenol. bm=unimproved base-material, M=Montigel, X=Tixosorb, P=Tixogel VP.

The compaction tests showed no significant differences in the standard Proctor density and corresponding optimum water content when the type of bentonite admixture was considered. The values averaged γ_d=20.25 kN/m^3 and w_{opt}=9.5 %.

The concentration profiles within the samples and the corresponding apparent diffusion coefficients are shown in Fig. 4. Within 17 days of diffusion, the phenol front migrated approximately 14 mm into the base-material improved with Tixogel VP (bmP graph in Fig. 4) and 19 mm into the base-material improved with Tixosorb (bmX graph in Fig. 4). After three days, the diffusion front migrated approximately 16mm into the base-material improved with Montigel (bmM graph in Fig. 4), 10mm in the unimproved base-material was contaminated to a depth of 10mm (bm graph in Fig. 4). The diffusion in the unimproved base-material respectively the base-material improved with Montigel was 3 to 6 times faster than for the samples improved with Tixosorb, and 6 to 12 times faster than for the base-material improved with Tixogel VP.

phenol concentration (C/Co)

direction of diffusion

- ☐ bm, t=3 d, D=3.8E-11 m2/sec
- ◇ bmM, t=3 d, D=8.1E-11 m2/sec
- △ bmX, t=17d, D=1.3E-11 m2/sec
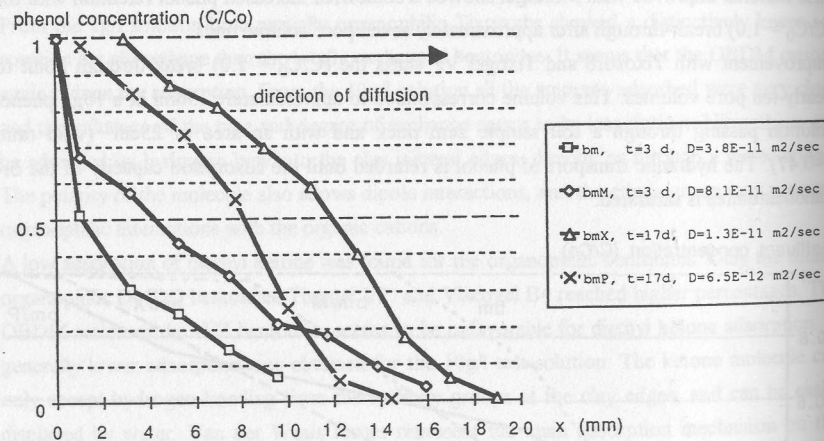- ✕ bmP, t=17d, D=6.5E-12 m2/sec

x (mm)

Fig. 4: Concentration profiles of phenol in base material and improved materials. bm=unimproved base-material, M=Montigel, X=Tixosorb, P=Tixogel VP, t=diffusion time in days, D=apparent diffusion coefficient in m^2/s.

Table 3 shows the results of the hydraulic conductivity tests in the oedometer cells with a vertical load of σ_1= 200kN/m^2. The base material has a hydraulic conductivity for water and 10g/l phenol solution of approximately 10^{-8}m/s. Similar permeabilities were observed for the samples improved with organophilic bentonites. There were no considerable differences when water or

the phenol test solution permeated the samples. Addition of Montigel decreased the hydraulic conductivity to about 10^{-9}m/s. This is caused by the swelling of the Ca^{2+}-bentonite in water and the aqueous phenol solution. The organophilic bentonites did not swell in the aqueous environments and remained flocculated. If the permeability tests were to be carried out with a pure organic liquid, the organobentonites are expected to swell, while the hydrophilic Montigel flocculates.

Table 3: Hydraulic conductivities (m/s) for a vertical load of σ_1= 200kN/m^2

specimen description	hydraulic conductivity (m/s)	
	with water	with 10 g/l phenol solution
base-material	2.1·10^{-8}	1.5·10^{-8}
base-material with 5% Montigel	2.9·10^{-9}	2.8·10^{-9}
base-material with 5% Tixosorb	1.8·10^{-8}	2.2·10^{-8}
base-material with 5% Tixogel VP	2.7·10^{-8}	1.5·10^{-8}

The results for the unconfined compression tests and derived elasticity modulus (secant modulus) are summarized in Table 4. Due to cohesion in the hydrophilic clay, the sample improved with the hydrophilic Montigel showed the highest shear strength, followed by the sample improved with the semiorganophilic Tixosorb. The hydrophilic interlayers of Tixosorb were responsible for a remaining cohesion in the aqueous environment. The totally organophilic Tixogel VP (hydrophobic surfaces, no plasticity) and the unimproved base- material without considerable amounts of clay minerals (Ip=0) showed lower shear strengths. In accordance, the base-material with Montigel showed the lowest elasticity module and highest strain at failure due to the plasticity of the Ca-bentonite ($I_p \approx 100$). The unimproved base-material and the samples improved with Tixosorb and Tixogel VP showed higher stiffness and lower strain at failure which was in accordance to non-cohesive materials.

Table 4: Unconfined shear strength (kN/m^2) with corresponding strain at failure (%) and elasticity modulus (MN/m^2).

specimen description	unconfined shear strength (kN/m^2)	percent strain at failure (%)	modulus of elasticity (MN/m^2)
base-material with 5% Montigel	70	7.7	2.7
base-material with 5% Tixosorb	68	3.8	6.8
base-material with 5% Tixogel VP	56	3.1	5.2
base-material	51	2.9	6.3

Conclusions

The type of adsorbent, and the interlayer cation and the degree of exchange by alkylammonium ions control the adsorption behavior of organophilic bentonites. For a known pollutant, a suitable adsorbent may be selected by percolation tests. Practical applications are treatment of organically contaminated industrial waste water or cleaning of gases.

The hydraulic transport of organic compounds in samples improved with organo bentonites is retarded until the adsorption capacity of the organo bentonite is saturated. The diffusive transport was also considerably hindered and retarded by approximately one order of magnitude.

For this study, the amount of 5% bentonite improvement was arbitrarily chosen. It is obvious that the dosage of the bentonite admixture can be optimized according to the porosity and granulometry of any concerning base-material. This also optimizes the adsorptive contaminant retention and the retardation of diffusive transport mechanisms. It is imaginable to use organophilic bentonites together with hydrophilic bentonites for construction of waste deposit liners. The corresponding percental endowments can easily be determined using the laboratory tests described in this study, and valuable time for the life of a liner can be gained.

No reduction of the stability or strength of the material improved with 5% organobentonites was observed in the aqueous environment. Full-scale construction of liners with organobentonite admixtures should be possible without any particular arrangements or machinery.

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Einsatz von Stickstoff- und Quecksilberporosimetrie zur Ermittlung der Porenverteilung in kohlenwasserstoffkontaminierten Böden

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Zusammenfassung

Veränderungen im Mikrogefüge schluffiger Tone nach dem Kontakt mit unpolaren Kohlen-wasserstoffen wurden mit porosimetrischen Methoden erfaßt und resultierende Perme-abilitätsunterschiede dokumentiert. 100- bis 500-fach höhere Durchlässigkeiten von verdichteten tonigen Böden für die Kontaminanten i-Oktan und o-Xylol im Vergleich zur konventionellen Durchlässigkeit mit Aqua dest. können nicht ausschließlich auf rein viskositätsbedingte Unterschiede der Perkolate zurückgeführt werden, sondern stehen auch in direktem Zusammenhang zum neuen Porenspektrum.

1. Einleitung

Die Sanierung von Schadensfällen mit Mineralölen und deren flüssigen Verarbeitungsproduk-ten ist heutzutage ein wichtiges Aufgabengebiet in der Umwelttechnik. Tankstellenleckagen, Raffineriealtlasten und eine Vielzahl von Altlasten in der lösungsmittelverarbeitenden chemischen Industrie (DVWK, 1991) sind nur einige Beispiele für die umweltgefährdende Verunreinigung des Bodens und des Grundwassers.

Die große Zahl der Schadensfälle ist nicht erstaunlich, da diese Stoffe in großen Mengen transportiert, gelagert und eingesetzt werden.

Das Rückhaltevermögen und die Durchlässigkeit eines Bodens wird von mehreren physiochemischen Faktoren beeinflußt. Dominierende Größen sind hierbei die spezifische Oberfläche und die Porenverteilung.

Aufgrund der geringen Löslichkeiten unpolarer Schadstoffe in Wasser und des oftmals massiven Auftretens der Kontaminanten ist deren Verbreitung im Untergrund nicht immer in gelöstem Zustand, sondern auch in Phase zu beobachten. Zudem ist häufig mit einer erheblichen Residualsättigung des Bodens gerade in schluffig-tonigen Sedimenten zu rechnen. Nachfolgende Untersuchungen verdeutlichen den Einfluß dieser Schadstoffe auf das Mikro-gefüge toniger Böden am Beispiel zweier Modellkontaminanten, i-Oktan und o-Xylol.