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Par ailleurs, l'observation visuelle des deux échantillons à la sortie des cellules de lixiviation a permis de constater une dégradation des coulis par lessivage : perte de couleur, fragilité. Ce phénomène est plus marqué dans le cas des créosotes.

5.2.3. Comparaison des quantités lixiviées

Après le premier jour de percolation, le coefficient de RNV est sensiblement identique pour l'eau et les créosotes, respectivement 3,5 et 3,6. Les quantités lixiviées sont alors similaires pour les deux fluides de percolation. La différence de comportement des coulis entre eau et créosote apparaît dès le troisième jour de l'expérience puisqu'elle est liée à la fréquence de renouvellement de l'eau des pores. Cependant, pour des RNV identiques, ce sont les ions calcium et silicium qui sont les plus sensibles à la solubilisation par les créosotes.

6. Conclusion

Cet article ne présente que les résultats obtenus sur un couple Coulis/Solution de percolation.

Les essais dynamiques de lixiviation par percolation, contrairement aux essais statiques en immersion, font apparaître des différences de comportement entre les coulis en fonction de la solution utilisée.

Les cinétiques de dissolution des coulis varient en fonction du type de coulis, de sa perméabilité et de la nature de la solution de percolation.

La détermination de la composition des matériaux à mettre en oeuvre passe désormais par la réalisation en laboratoire d'essais sévères de détermination de pérennité.

Les résultats montrent que les deux tests, percolixiviation et immersion, doivent être réalisés simultanément car l'action des produits chimiques procèdent de processus différents dans les deux cas.

Les conséquences sur la stabilité mécanique et sur les variations éventuelles du coefficient de perméabilité diffèrent selon le mode de transport des produits.

Cette nouvelle approche de la détermination de la composition des coulis a été adoptée systématiquement pour la réalisation de plusieurs coupures d'étanchéité destinées à prévenir de l'extension de pollutions potentielles.

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Effects of Leachate on the Hydraulic and Mechanical Behaviour of Clay Liners

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Abstract. In addition to water content, degree of saturation, effective pressure and stress history, the hydraulic and mechanical behaviour of clay also depends on its mineralogy and the chemical compounds of the pore-fluid. This fact is fundamentally due to ion exchange and mineral dissolution phenomena occurring between clayey minerals and cations existing within the fluid. This paper deals with a laboratory investigation on the behaviour of four different sand-bentonite mixtures, alternatively permeated with water and leachate. A sodium bentonite and a calcium bentonite were used in order to emphasize the effects caused by different clay minerals. Fixed-wall permeability and oedometer compression tests were carried out; the influences of void ratio, vertical effective pressure and permeant on hydraulic conductivity, compressibility and consolidation coefficients of clayey samples were investigated.

Introduction

The design of urban solid waste disposals needs to solve many important geotechnical problems. If any impervious natural layers do not exist on the site, barriers to fluids must be made in order to avoid pollution of the surrounding environment. The impermeabilization of bottom and sides of a disposal area must be made using economical materials which are able to maintain their impervious function for at least some decades. Impervious liners can consist of compacted clays, clay-sand mixtures, geosynthetic-clays and geomembranes.

When clay-sand mixtures are exploited, bentonitic clays with a significant montmorillonitic component are preferable. The cost of the mixture usually depends on the amount of the bentonite used. Even relatively low percentages of bentonite ($\approx 9\%$) in a compacted clay-sand mixture allow permeability coefficients lower than $1E-10$ m/s to be obtained [1]. The effectiveness of the clay lining in preventing movement of leachate depends on its

ability to maintain a very low permeability while in contact with contaminated fluids. Permeant passing through fluid barriers is generally chemically different from test fluids (water) used in laboratory investigations. So an unexpected increase in liner permeability could also increase the seepage of the leachate through the clay liner. Furthermore an increase in compressibility of the clayey layers involved could cause unexpected settlements of the site.

The hydraulic and mechanical behaviour of clayey soils strongly depends on their fabric and on the chemical nature of the permeant fluid. For example, large differences in hydraulic conductivity were noticed using water or leachate as permeant for the same clay [2]. This behaviour seems to be related to ionic exchange and mineral dissolution processes, occurring between clay minerals and chemical compounds of fluid. As a consequence of these physico-chemical interactions the double layer thickness of clay particles could increase or decrease. Increases in hydraulic conductivity may occur because the soil

structure is more flocculated and the soil porosity is higher; otherwise if the thickness of the double layer decreases the hydraulic conductivity should increase.

Dissolution of soil minerals can occur under adverse pH conditions, with caustics tending to degrade the silica tetrahedra and acidic permeants causing dissolution of the octahedral layer [3].

Results of laboratory investigations are presented in this paper in order to emphasize in particular the influences of bentonite-sand content and fluid chemistry on the mechanical and hydraulic behaviour of clayey soils.

Investigation and results

Laboratory tests are generally used to determine the hydraulic conductivity of clays. They may be performed with either fixed- or flexible-wall permeameters using constant or falling head methods. A detailed analysis of the advantages and disadvantages of fixed- and flexible-wall permeameters are reported in [4,5].

Three natural soils were considered: a sodium bentonite (K7), a calcium bentonite (C), and a uniform sand. Their main index properties and chemical compounds are briefly summarized in Table 1 and 2 respectively. Laboratory tests were carried out on sand-bentonite mixtures, prepared in the laboratory with different weight percentages, in order to test samples having varying plasticity.

Their Atterberg limits are reported in Table 3.

The natural soils were first completely dried, then mixed using different amounts of natural soils, wetted with water (the resulting moisture content was 1.5 times its liquid limit) and were finally homogenized by hand. After mixing the slurry was covered and allowed to hydrate for a week.

The fully hydrated sand-bentonite-water slurry was placed in oedometric consolidation cell, 70 mm wide and 20 mm high. Care was taken to remove as much air as possible, placing small amounts of soil at a time and vibrating it. Conventional step-loaded oedometer tests with permeability determination were carried out.

TABLE 1. The main index properties of soils

SOIL	W _l (%)	W _p (%)	I _p (%)	G _s	A
K7 - Bentonite	346	56	290	2.70	4.3
C - Bentonite	115	83	32	2.75	1.3
Adige River Sand	-	-	-	2.71	-

TABLE 2. Chemical compounds of bentonites

Chemical Compounds	Bentonite C (%)	Bentonite K7 (%)
SiO ₂	48.40	58.88
Al ₂ O ₃	21.05	14.62
Fe ₂ O ₃	11.50	5.56
TiO ₂	3.20	=
MnO	0.11	=
CaO	3.45	1.09
MgO	0.45	1.36
Na ₂ O	0.31	0.96
K ₂ O	0.40	1.20
H ₂ O	11.80	16.02
Montmorillonite (%)	70	80 to 90

TABLE 3. Index properties of test mixtures

MIXTURE	W _l (%)	I _p (%)
A (C 50% - S 50%)	58	20
B (K7 30% - S 70%)	61	37
C (K7 20% - S 80%)	46	21
D (K7 10% - S 90%)	31	14

After a 24 hour consolidation stage for each step, a head difference of 3 m was applied between the

two ends of the sample, connecting its bottom to a 5 mm diameter burette filled with the test permeant. Two pore volumes of permeant fluid were filtered through the sample before starting each test. A falling head permeability test was then performed. During the test, readings of the decrease in hydraulic head over time were recorded for a period of 24 to 48 hours. Vertical permeability was calculated from the following falling head equation:

$$k = \beta \cdot \ln\left(\frac{h_0}{h_t}\right) \cdot \frac{a \cdot L}{A \cdot \Delta t} \quad (1)$$

where β is a correction factor, depending on the dynamic viscosity and temperature of the test fluid, a and A are the cross-sectional areas of the burette and sample respectively, L is sample height, h_0 and h_t excesses of hydraulic head at time $t=0$ and after time Δt respectively. It was assumed that flow is governed by Darcy law, the steady state condition is established immediately, the permeability is uniform and remains constant throughout the test.

Two pore fluids were used as permeants to investigate their effects on the hydraulic conductivity of mixtures: (1) deaired distilled water; (2) a suitable caustic leachate, whose main chemical compounds (Table 4) are similar to those produced by an urban waste disposal. A rotational viscometer was used to evaluate permeant viscosity with temperature ranging from 10 and 30°C and shear rate from 0 to 300 s⁻¹. Scattering was less than 6%. Natural water was used both for mixing and initial permeation.

The compressibility curves e -log σ' derived from tests with different mixtures and permeants are plotted in Fig.1 a, b. The calcium bentonite-sand mixture (A) shows a compressibility independent on permeant in the range of investigated pressure, whereas mixtures containing sodium bentonite (mixtures B, C, D) show a certain dependence on the permeant. The compressibility index C_c ranges from 0.17 to 0.82 for samples filtered by water, and from 0.39 to 1.35 for samples filtered by leachate (Table 5).

This is due to the higher colloidal activity of sodium bentonite in comparison with calcium bentonite. Furthermore the calcium cation proves very capable of holding montmorillonite sheets together, therefore calcium bentonite generally presents a slight tendency to swelling.

TABLE 4. The main chemical compounds of the leachate (pH=10)

LEACHATE	MOL/LITRE
NH ₄ ⁺	5.0 x 10 ⁻²
Na ⁺	8.8 x 10 ⁻²
K ⁺	2.2 x 10 ⁻²
Ca ²⁺	6.1 x 10 ⁻³
Mg ²⁺	1.0 x 10 ⁻³
Cd ²⁺	1.0 x 10 ⁻⁶
Cl ⁻	1.0 x 10 ⁻⁷
NO ₃ ⁻	2.0 x 10 ⁻³

TABLE 5. Compression index of the test samples

MIXTURE	C _c - water	C _c - leachate
A	0.42	0.39
B	0.82	1.35
C	0.49	0.60
D	0.17	0.39

Vertical coefficient of consolidation c_v remains nearly constant with varying vertical pressure (Fig.2 a,b). However the c_v -coefficients of samples filtered by leachate is always higher than those of samples filtered by water. The permeability test results are plotted in Fig.3 a, b, c, d. The hydraulic conductivity strongly depends on void ratio, decreasing when it also decreases. The relation between hydraulic conductivity and void ratio on a

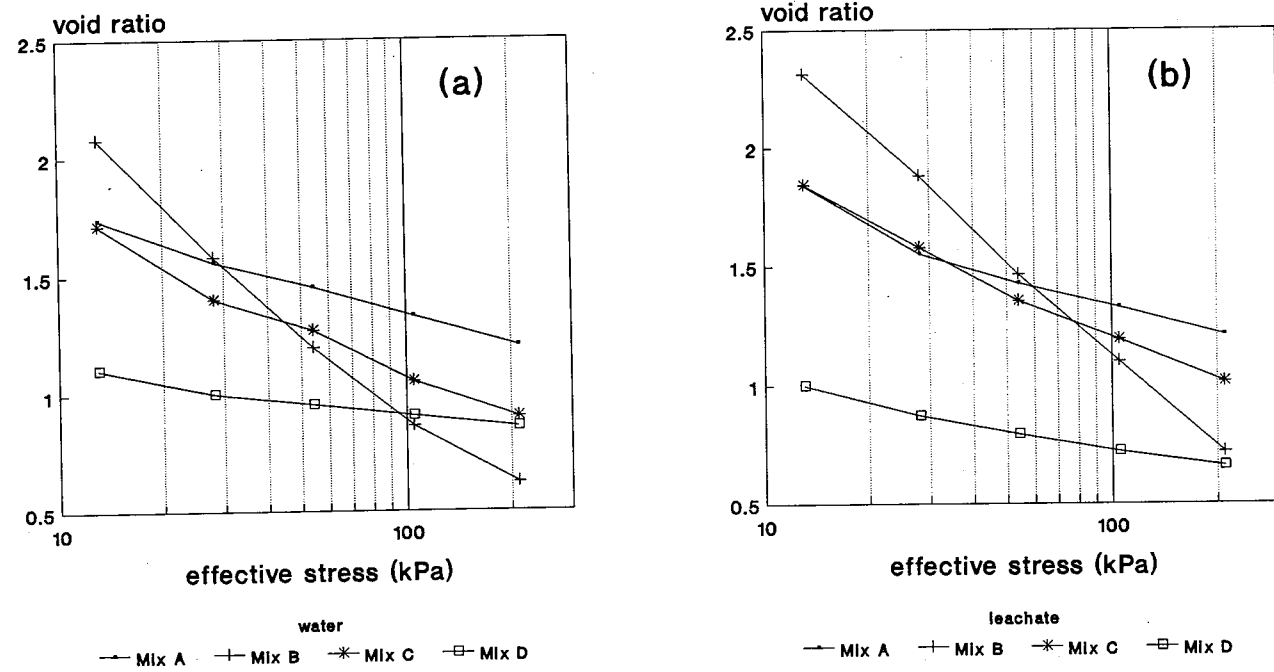


Fig. 1 a,b. Void ratio vs. effective vertical stress curves

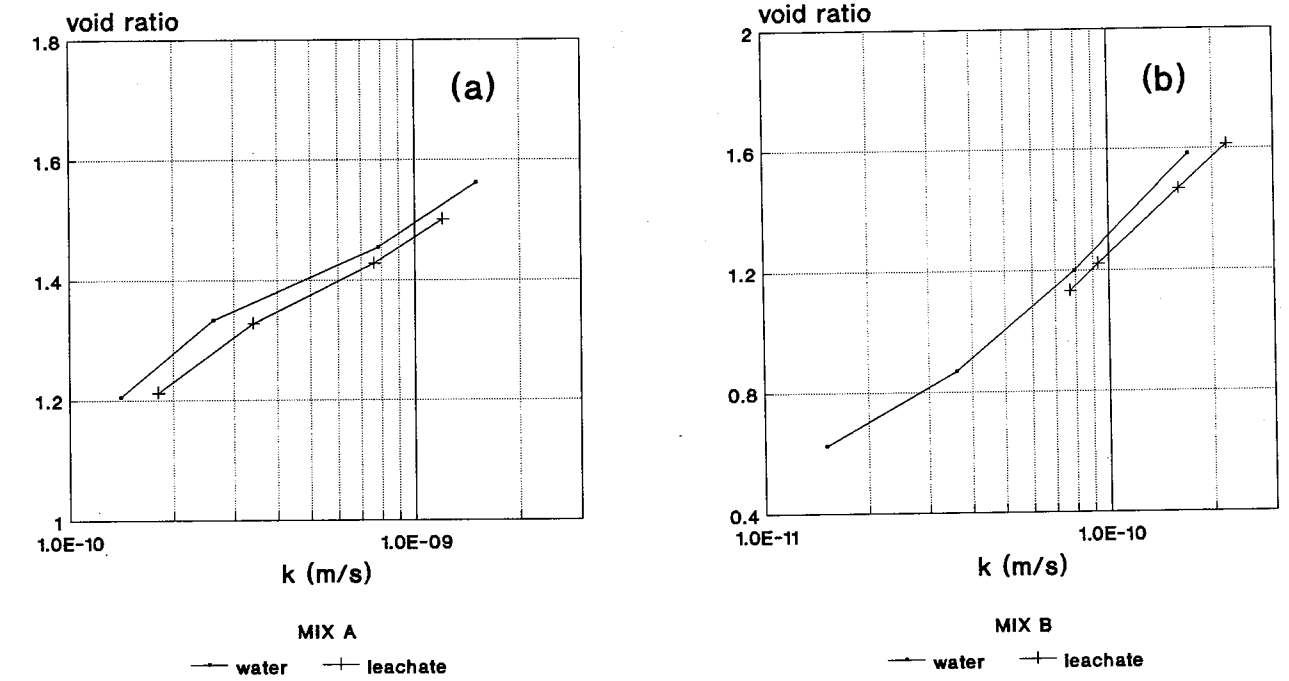


Fig. 3 a,b,c,d. Void ratio vs. hydraulic conductivity curves

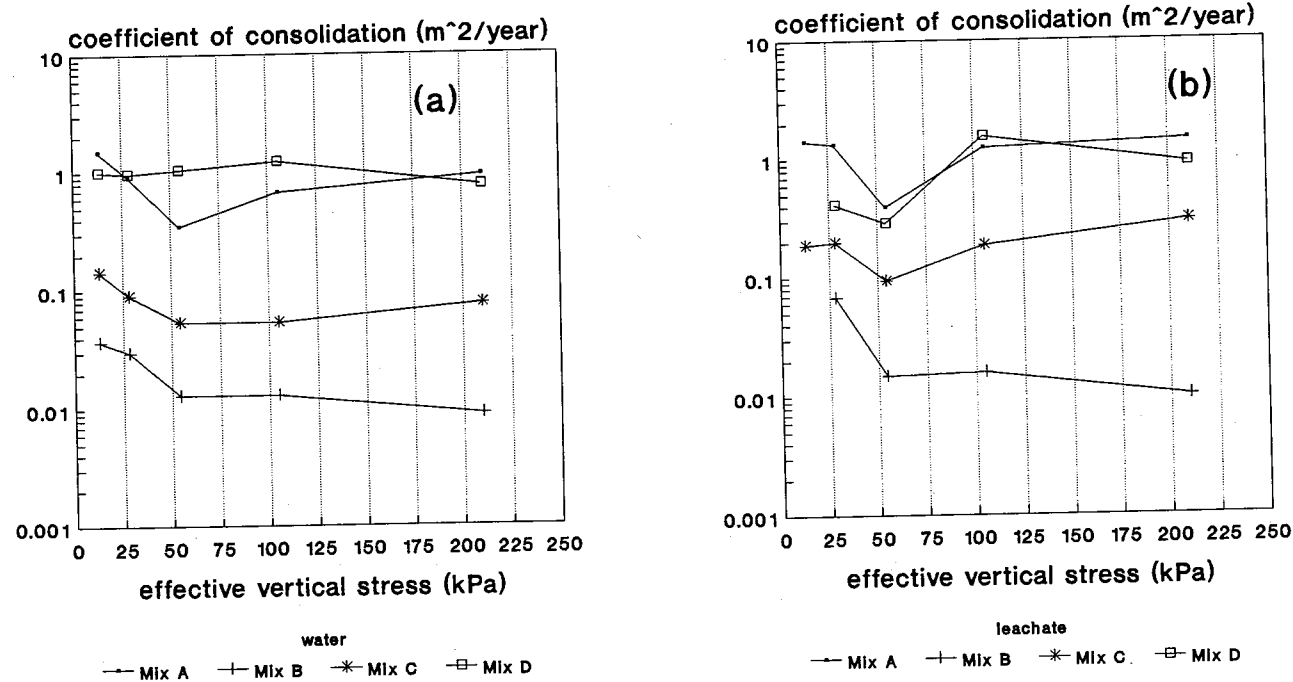


Fig. 2 a,b. Coefficient of consolidation vs. effective vertical stress curves

semi-logarithmic diagram is nearly linear: its slope can be determined by the following expression:

$$C_k = \frac{\Delta e}{\Delta \ln k} \quad (2)$$

The mixture A shows the same slope for both permeants. The sodium bentonite-sand mixtures show steeper slopes when they were filtered by leachate (Table 6).

TABLE 6. Slope of e -log σ' plots

MIXTURE	C_k water	C_k leachate
A	0.33	0.33
B	0.90	1.10
C	0.71	0.90
D	0.56	0.76

The hydraulic conductivity of samples filtered by water is always less than that determined with leachate, whereas it seemed not to be dependent on the applied gradient, according to Darcy's law.

Conclusions

Test results showed that sodium bentonite-sand mixtures, saturated and filtered by caustic leachate, present chemical activity which influences the soil structure and causes high compressibility and low hydraulic conductivity. Calcium bentonite-sand mixture showed low compressibility and high

permeability, because of its capacity to produce stable structure.

Further laboratory tests, performed with oedometric and triaxial equipments, using acid and neutral leachates are carrying out on sand-bentonite mixtures in order to evaluate the effects of permeant on the behaviour of clayey soils.

Acknowledgment

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A New Apparatus for the Measurement of Water-Air Permeabilities

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Abstract : The paper presents a new apparatus, based on the air pressure technique, for the measurement of water-air polyphasic permeabilities in soils. Three examples of measurements on remolded clayey soils are shown, which point out the important hysteresis between the drying and wetting paths. The comparison of the values of negative pressure for which the water permeability becomes nought, with those of the shrinkage limit highlights the correspondence between the two parameters.

1. Introduction

The study of polyphasic flows in porous media of average permeability is still dominated by the concept of relative permeabilities, first introduced by the petroleum engineers in the '30 [1, 2]. Later, Iffly [3] and others showed that Darcy's law was not valid for gases, even in the case of monophasic flows, while additional problems were encountered in polyphasic flows (end effects, etc.). Schwartzendruber [4], Hadas [5], Nimmo [6] tried to establish the laws describing the flow of water in unsaturated soils. These researches did not lead to very definite conclusions, mainly due to the complexity of the experimental device and procedures. On the other hand, questions arise concerning the validity of Darcy's law for water in the case of clays of very low permeability - e.g. "swelling" clays used as barriers for the storage of nuclear wastes. New approaches have been devised, in which the flow mechanism is associated with a diffusion mechanism that may play the major part [7, 8].

In most cases, however, the polyphasic permeabilities can still be obtained with reasonable accuracy by postulating a flow law and measuring the corresponding coefficients. Two methods are currently used to measure these permeabilities:

- the *unsteady state* method, in which a flow of air or water is imposed on one end of the sample and the change in the state of the material (void ratio, water content) is measured during the advance of the front,

- the *steady state* method, in which both fluids are injected simultaneously at both ends of the sample in such a way that the state of the sample is not modified by the flow.

The first method can be used only if it is possible to measure the local soil parameters at all points (e.g. with a radiographic device [9]), as well as the local pressure gradients. To derive the permeabilities, the measured water content or density profiles must be fitted by means of a computer code, which is often difficult. However, this kind of test can be carried out in the usual triaxial cells.

On the other hand, in the steady state method, the permeabilities are derived directly from the measurements, at least for materials of low deformability, as all the parameters of the sample remain constant during the test. Conversely, the experimental device is complicated by the fact that the flows of water and air must be separated, outside the sample, by semi-permeable membranes.

In fact, in the case of highly plastic or highly compacted materials, in which large strains may develop during drying or wetting, the use of this technique becomes much more complex, due to the fact that a constant negative pressure does not lead to a constant degree of saturation: if the deformation of the sample is prevented during the wetting phase, a swelling pressure will develop and modify the state of the soil; on the other hand, during the drying phase, the deformation of the sample may result in the formation of a void between the sample and the wall of the cell, which will greatly perturb the measurements.