7th International IAEG Congress / 7ème Congrès International de AIGI, © 1994 Balkema, Rotterdam, ISBN 90 5410 503 8

Permeability tests on kaolinite and a natural clay liner
Essais de perméabilité sur kaolinite et sur une membrane de sol argileux naturel

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ABSTRACT: A programme of laboratory tests has been undertaken to investigate the change in permeability of clayey soils due to exposure of saline solutions. Remoulded samples of commercially available kaolinite and of a natural soil, occurring at the base of Coimbra sanitary landfill, were prepared using distilled deaired water and salt solutions at varying concentrations. The permeability tests were performed in consolidated samples using a reducing head permeameter. The results showed no significant changes in permeability due to the increase of the chemical solutions concentration.

RÉSUMÉ: On a executé un programme d'essais en laboratoire pour investiguer les altérations de perméabilité deux sols argileux soummis à des solutions salines. On a préparé des échantillons de kaolinite et de sol naturel qu'on a trouvé dans le enfouissement sanitaire de Coimbra, en employant de l'eau distilée et salées à des concentrations varieés. Les essais de perméabilité ont eté faits sur des échantillons consolidés à l'aide d'un perméamètre à charge réductice. Les résultats de ce programme montrent que les changements de perméabilité aucun accroissement des concentrations salines soient devenus négligeables.

1 INTRODUCTION

The disposal of waste materials is a matter of increasing public concern. Sanitary landfills were conceived to minimise the risk of pollution due to waste disposal contaminants. However, the construction of sanitary landfills, in sites where the geologic and hydrogeologic features do not guarantee an environmental protection, requires the installation of a lining system. To be efficient the sealing soils that are a part of the lining system, should have low permeability and should not change under the action of the leachate. To investigate the influence of chemical solutions on the permeability of clayey soils laboratory tests were performed. The soil samples were prepared either with distilled and deaired water (DDW) or with salt solutions. Potassium nitrate and potassium sulphate were the salt solutions used in the tests. The nitrate and sulphate anions were chosen because both can be founded in leachates from sanitary landfill (Attewell, 1993; Yong et al., 1992), and the potassium cation was chosen in both cases to reduce the number of variables. The samples were firstly consolidated, under different vertical stress, and then the permeability tests were carried out in a reducing head permeameter.

This paper reports: the permeability changes with the salt solution concentration; the influence of increasing consolidation pressures on permeability; and the soils permeability using DDW compared with those using salt solutions.

2 EXPERIMENTAL PROGRAM

In this work two different soils were used, a commercially available kaolinite in a powder form and a natural occurring soil. These soils were initially classified through index tests and results are summarised in table 1.

The natural soil was firstly pulverised, by using a pestle, and the particles larger than 4.76mm were removed according to BS:1377:Part 6:1990.

Table 1 - Results of the index tests

	Kaolinite	Natural clay
% gravel	-	5.6
% sand	-	34.4
% silt	-	32.0
% clay	100	28.0
W_L (%)	60	49
W_P (%)	33	25
$I_P=W_L-W_P$	27	24
G_s	2.59	2.49
Classification (Plasticity Chart)	MH	CI

The samples for the consolidation tests were prepared by mixing the dry kaolinite or natural soil with DDW, potassium nitrate (KNO_3) and potassium sulphate (K_2SO_4) at a high moisture content (approximately equal to the liquid limit of the soils). After mixing, the slurry was sealed in a polythene bag for 24 hours to homogenate and in the next step was placed in a special cell for consolidation (figure 1). The cell was designed to carry out the consolidation and permeability measurements.

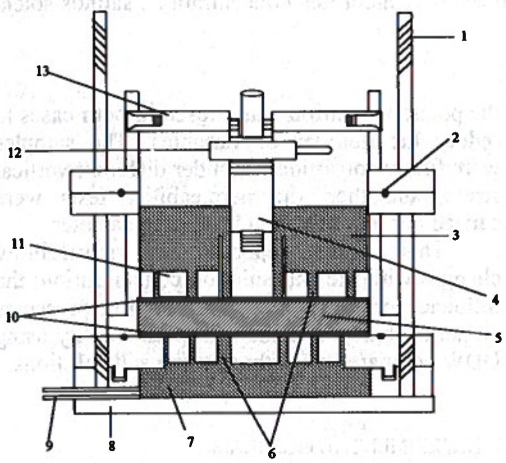

Figure 1- Cross section of the permeability cell. (1) Connecting rod; (2) o-ring (3) solution; (4) piston; (5) sample; (6) drainage holes; (7) solution; (8) base; (9) tap; (10) porous disc; (11) loading disc; (12) thumb screw; (13) top cell piece; (modified from McDermott and Selby, 1990).

Care was taken to remove the air from the samples. Each sample was 100 mm diameter and 30 mm thick and was consolidated under different stress of 50, 100, 200 or 400 kPa. The vertical load was applied and maintained until the primary consolidation finished (usually 24 hours). Before removing the vertical load the thumb screw on the piston was tightened up to avoid swelling of the soil samples.

Then the cell was set up with a cell top plate and connected, in the top, to the pressure chamber and in the bottom with the burette. The system was carefully deaired and filled either with DDW or with chemical solutions at selected concentration. Whole soil samples were immersed in fluid solution appropriate to the particular test. The solutions of potassium nitrate and potassium sulphate were prepared in agreement to molarity principles at 0.001M, 0.01M and 0.1M concentrations. Permeability determinations were then carried out on a reducing head permeameter (figure 2).

This permeameter was designed to test very low permeability soils. An air pressure applied in the bladder and controlled by regulator valve was used to exert a required pressure upon the solution. It was then transmitted at the top of soil samples provoking a flow through the sample and up into the burette. During the tests readings of reducing head were taken as a function of the time. A solution movement of more than 200 mm was always required before the test was considered complete. The permeability was calculated for each load applied during consolidation.

It was assumed that the specimen was fully saturated and the flow was governed by Darcy's law. Therefore the permeability coefficient (K) was calculated from the falling head equation considering the effective pressure head values:

$$K = 2.3\frac{al}{At}\log_{10}\frac{h1}{h2}, \text{ where} \qquad \text{(Eq. 1)}$$

a - is the cross sectional area of the burette in mm^2

A - is he cross sectional area of the soil in mm^2

l - is the length of sample in mm

h_1 and h_2 are the differential heads in mm, at the start and finish of the time interval (*t*)

t - time in seconds

Once the permeability test was complete the cell was disconnected from the system. The final thickness of the sample was recorded and the moisture content determined. The results were then used to calculate the void ratio of the samples.

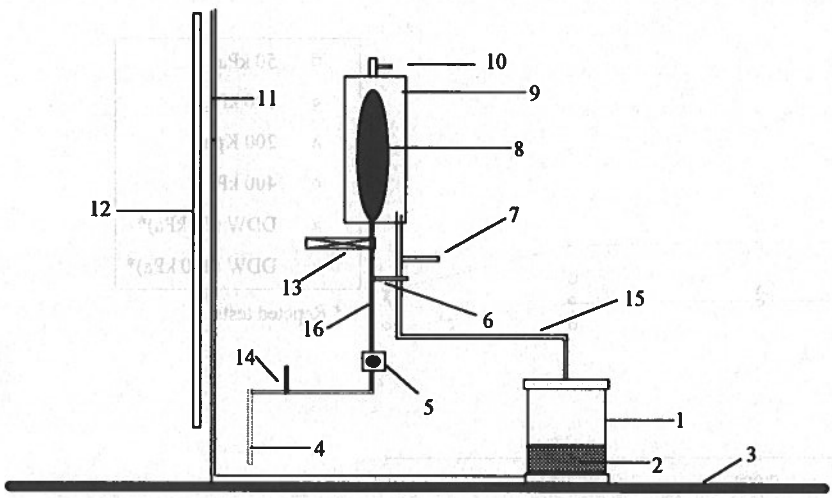

Figure 2 - Reducing head permeameter. (1) Consolidation/permeability cell; (2) sample; (3) base; (4) compressed air supply; (5) air pressure regulator; (6) security valve; (7) connection valve; (8) bladder; (9) DDW or solution tank; (10) solution inflow; (11) burette; (12) meter rule; (13) pressure transducer; (14) air valve (15) solution pipe; (16) air pipe.

3 RESULTS

The permeability results obtained from the experimental work are summarised in figures 3, 4, 5 and 6. A logarithmic scale was used for the permeability values. In each figure a upper and lower bound are plotted which correspond to the lowest (50kPa) and highest pressures (400kPa).

First to be examined was the influence of increasing salt solutions concentrations on permeability. DDW, potassium nitrates and potassium sulphate at 0.001, 0.01 and 0.1 M concentrations were used. The results showed only very small permeability changes with the increase of the chemical concentrations. However, the kaolinite showed a decrease on permeabilities with both solutions especially after the concentration exceeded 0.01M. The natural soil showed a slight reduction in permeability with increasing potassium sulphate; conversely, the soil showed increased permeability with higher concentrations of potassium nitrate. There was no obvious reason to explain the opposite trends presented by kaolinite and natural soil

Permeability tests performed by McDermott (1989) on different soils (kaolinite, montmorilonite, ilite and a naturally occurring soil) to sodium nitrates revealed some small permeabilities changes with increasing salt solutions. In that work only montmorillonite showed a significant change in permeability as function of increasing solutions concentrations. This was explained by the anionic exchange of hydroxyl ions within the montmorillonite minerals for nitrate ions. Similar results were obtained by Hawthorn (1991) using the same soils as McDermott with aluminium sulphates.

Then was analysed the permeability change as function of increasing vertical stress. The consolidation pressures used were 50, 100, 200 and 400 kPa. It was noteworthy that for the same consolidation pressure the void ratios found showed a repeatable result, as presented in tables 2 and 3. This was true for the kaolinite and the natural soil. The repeatable void ratios were an essential requirement for the test program. Throughout the experiments the void ratio for each soil sample, at the same consolidation pressure, showed no significant variation and hence no important change in permeability can be attributed to the void ratio.

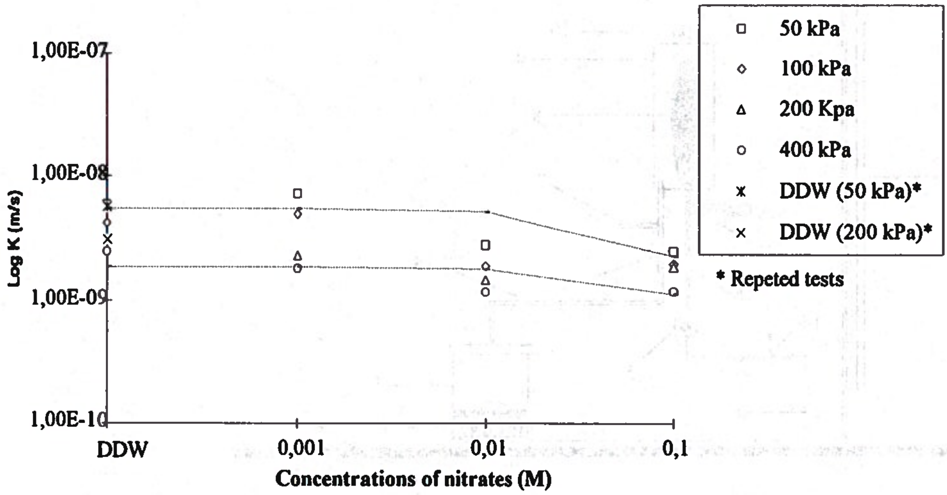

Fig. 3 - Permeability results of the kaolinite soil using DDW and potassium nitrate.

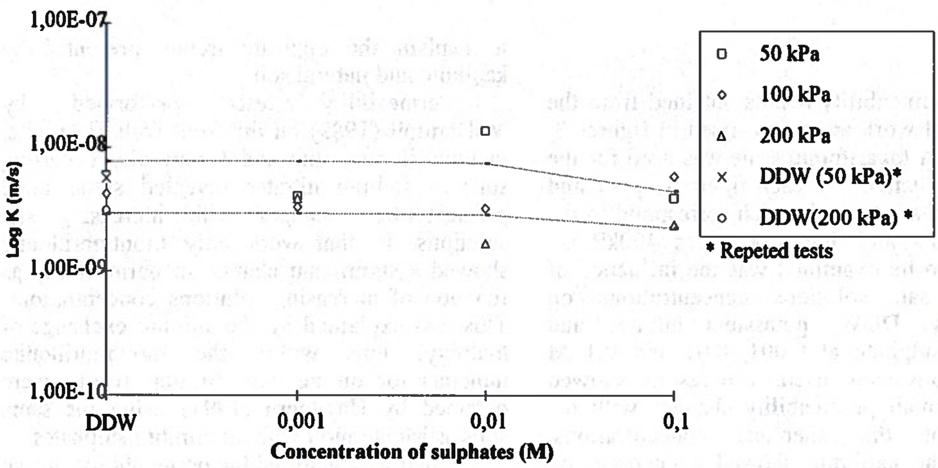

Fig. 4 -Permeability results of the kaolinite soil using DDW and potassium sulphate.

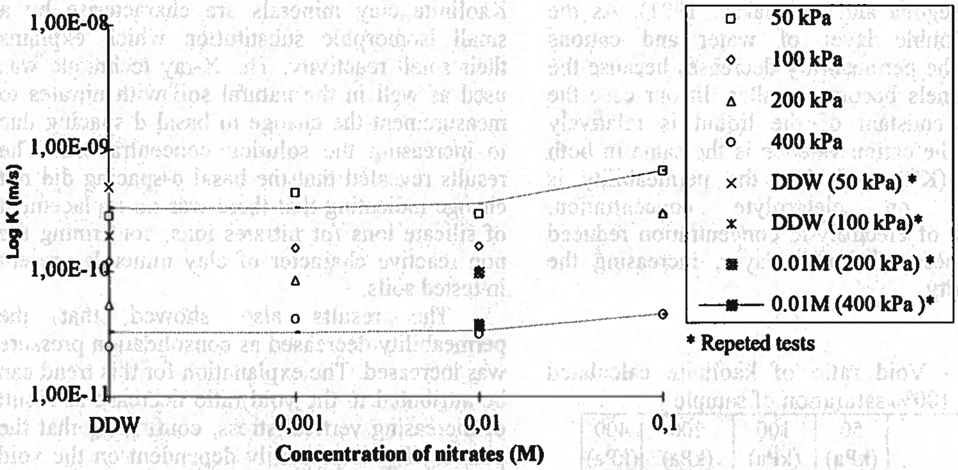

Fig.5 -Permeability results of the natural soil using DDW and potassium nitrate.

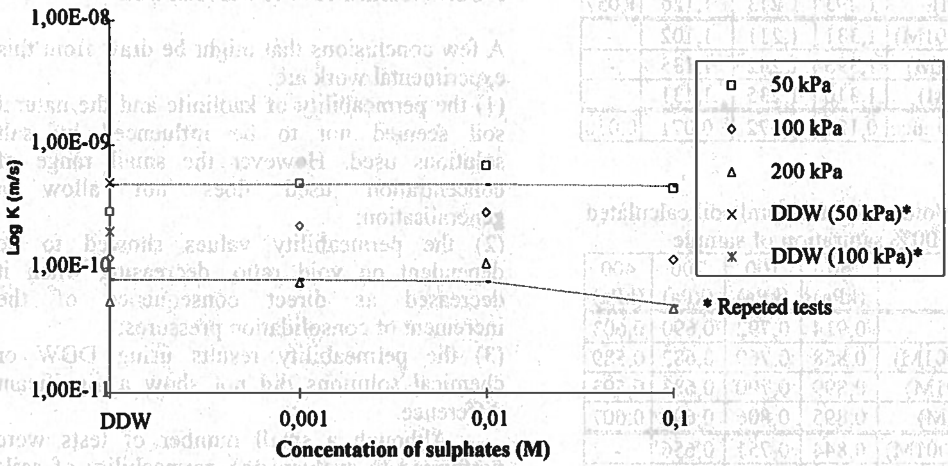

Fig. 6 - Permeability results of the natural soil using DDW and potassium sulphate.

Some permeability tests were repeated under the same conditions with the same solution concentration. They were performed to ensure that the method was accurate. Repeated tests showed a reproducible result.

4 DISCUSSION

The effects of salt solutions on permeability of clay soil can be evaluated with Gouy-Chapman theory (Mitchell, 1976 refereed Daniel and Shackelford, 1987) which states that the thickness of double diffuse layer (t) varies with the dielectric constant of the pore fluid (ε), the electrolyte concentration (n_0) and the cation valence (z) as follows:

$$t \propto [\varepsilon/(n_0 z^2)]^{1/2} \quad \text{(Eq.2)}$$

Change in permeability due the chemical solutions is attributed to the change in soil structure due to the change in double diffuse layer (Meegoda and Rajapakse, 1991). As the diffuse double layer of water and cations expands, the permeability decreases because the flow channels become smaller. In our case the dielectric constant of the liquid is relatively constant, the cation valence is the same in both solutions (K^+), and thus the permeability is dependent on electrolyte concentration. Increasing of electrolytic concentration reduced the thickness of double layer, increasing the permeability.

Table 2 - Void ratio of kaolinite calculated assuming 100% saturation of sample

	50 (kPa)	100 (kPa)	200 (kPa)	400 (kPa)
DDW	1,333	1,274	1,173	1,082
KNO_3 (0.001M)	1,416	1,283	1,168	1,079
KNO_3 (0.01M)	1,380	1,251	1,135	1,026
KNO_3(0.1M)	1,293	1,213	1,126	1,057
K_2SO_4 (0.001M)	1,331	1,211	1,102	-
K_2SO_4 (0.01M)	1,395	1,242	1,135	-
K_2SO_4 (0.1M)	1,316	1,235	1,131	-
Largest difference	0,123	0,072	0,071	0,056

Table 3 - Void ratio of natural soil calculated assuming 100% saturation of sample

	50 (kPa)	100 (kPa)	200 (kPa)	400 (kPa)
DDW	0,914	0,792	0,690	0,603
KNO_3 (0.001M)	0,858	0,769	0,682	0,589
KNO_3 (0.01M)	0,899	0,790	0,683	0,593
KNO_3 (0.1M)	0,895	0,806	0,699	0,607
K_2SO_4 (0.001M)	0,844	0,751	0,656	-
K_2SO_4 (0.01M)	0,848	0,760	0,672	-
K_2SO_4 (0.1M)	0,834	0,805	0,713	-
Largest difference	0,080	0,055	0,057	0,018

We consider that the small permeability changes presented by the tested soils were due:
(1) to the low concentrations used which were not effective to change the thickness of double layer and thus were not able to change substantially the permeability.
(2) to the non reactive nature of clay minerals mainly present in these soils. X-ray analysis, performed to assist in the interpretation of the results, showed that kaolinite was the clay mineral predominant in both soils that reached 90% in kaolinite (McDermott and Selby, 1990). Kaolinite clay minerals are characterise by a small isomorphic substitution which explains their small reactivity. The X-ray technique was used as well in the natural soil with nitrates to measurement the change in basal d spacing due to increasing the solution concentrations. The results revealed that the basal d-spacing did not change indicating that there was no replacement of silicate ions for nitrates ions, confirming the non reactive character of clay minerals present in tested soils.

The results also showed that the permeability decreased as consolidation pressure was increased. The explanation for this trend can be attributed to the void ratio decrease as result of increasing vertical stress, confirming that the permeability is primarily dependent on the void ratio (Favaretti and Moraci, 1991).

5 CONCLUSIONS AND FINAL REMARKS

A few conclusions that might be draw from this experimental work are:
(1) the permeability of kaolinite and the natural soil seemed not to be influenced by salt solutions used. However the small range of concentration used does not allow a generalisation;
(2) the permeability values showed to be dependent on void ratio, decreasing when it decreased as direct consequence of the increment of consolidation pressures;
(3) the permeability results using DDW or chemical solutions did not show a significant difference.

Although a small number of tests were performed to evaluate the permeability of soils with salt solutions as permeants, it appears that permeability of the two soils tested is much more affected by the density of the soils than the nature of pore fluid. From a practical point of view this is very important since that the protection of ground water could be guaranteed to small concentrations of salt solutions. The authors suggest that more tests of similar nature should be carried out using if possible real leachates, and montmorillonite rich soils.

ACKNOWLEDGEMENTS

The authors wishes to thank to the University of Durham to the valuable cooperation in the

experimental work and the helpful assistance of technician of Soil Mechanics Laboratory.

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