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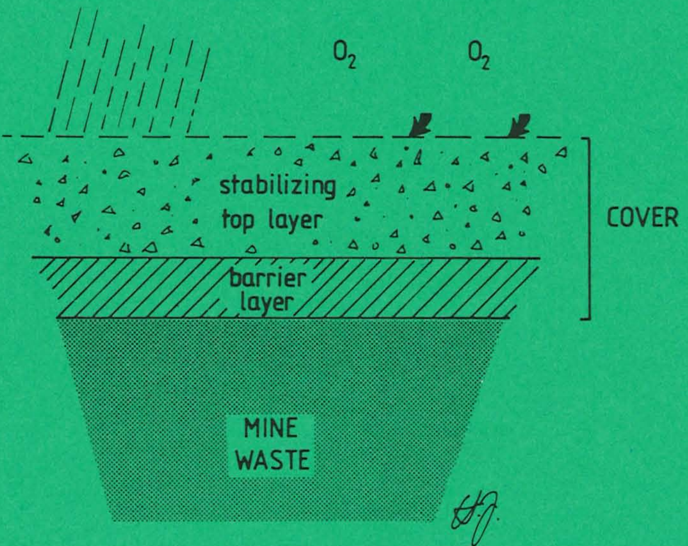
AIR AND WATER MOVEMENT IN COVERS FOR MINE WASTE

Syre- och vattenbarriäregenskaper hos täckmaterial för gruvavfallsmagasin

Jan Lindström
Mary Mc Afee



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Rapport 153
Report

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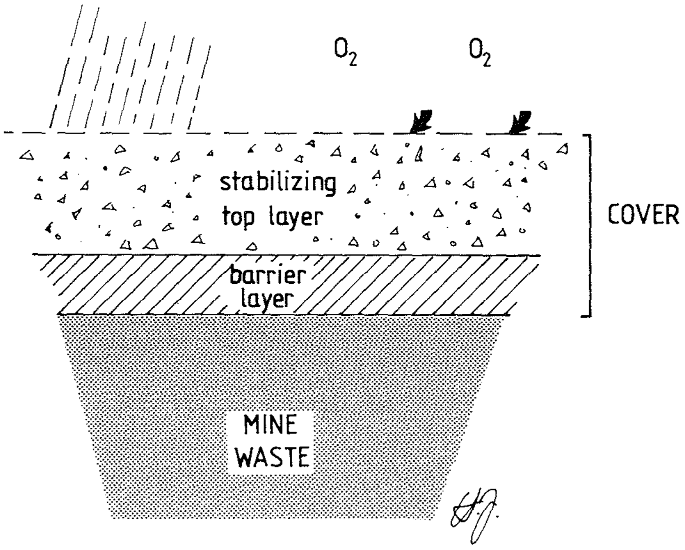

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BACKGROUND

This investigation forms part of a larger project initiated by the Swedish Board for Environmental Protection. The aim of the project is to develop methods of dealing with minewaste dumps so as to reduce the risk of damage to the environment. Weathering of the metal sulphide wastes which are the by-products of metal ore mining and purification occurs in the presence of atmospheric oxygen. It leads to production of sulphuric acid and metal ions are freed. Water percolating through mine waste is likely to be very acidic and is a serious pollutant.

One method of dealing with mine waste is to cover the dumps with a material which will prevent oxygen and rainwater from reaching the waste. Such barrier layers must be very impermeable and must have a very effective moisture retaining ability in order to prevent weathering and to reduce leaching.

The project mentioned above comprises both theoretical and practical investigations on possible constructions of the barrier layer and on the materials to be used.

Fig. 1 shows one proposed construction of such a barrier (Södermark, 1986).

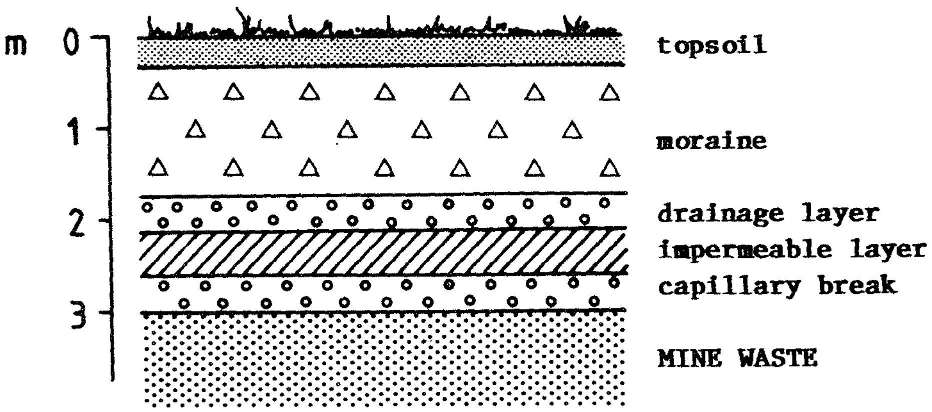

Fig. 1. Construction of barrier layer
Exempel på täckskikts uppbyggnad

This report deals with a number of practical investigations of possible barrier materials. Resistance to air and water movement in materials was tested in laboratory measurements of diffusion coefficient and moisture retention characteristics at a range of matric tension steps. All experimental work reported here was carried out at the Division of Agricultural Hydrotechnics, Swedish University of Agricultural Sciences. Apart from the practical application of the results obtained, in forming a basis for selection of barrier materials, this investigation had also a more general aim. This was to evaluate the method used for determining diffusion coefficient. This method had previously been applied to arable soil samples and drier samples (Edling, 1986). The range of air-filled porosities in the materials tested in this experiment was expected to be very low and few diffusion measurements have been made at low air contents (Bakker & Hidding, 1970). This is surprising since it is the critically low diffusion values which are of importance in agriculture. The results of this investigation are thus of interest both to those working with applied problems of mine waste storage and to those investigating diffusion in porous media in general.

MATERIALS

The materials tested in this experiment are listed in Table 1.

Table 1. Materials and mixtures tested as possible barriers to oxygen and water
Material och blandningar som ingick i denna undersökning

No.	Base	Inclusion % by wt.	Symbol	Desired bulk dens. g/cm^3
1	95% normal sand	5% bentonite	95s/5b	1.90
2	90% normal sand	10% bentonite	90s/10b	1.75
3	mine sediment ("svartmocka")	-	svm undisturbed	
4	clay ("torrskorpelera")	-	tsl undisturbed	
5	coarse waste sand	-	cws	2.00
6	90% coarse waste sand	10% bentonite	90cws/10b	1.75
7	90% weathered waste sand	10% bentonite	90wws/10b	1.75
8	fine waste sand	-	fws	1.90
9	moraine from Bergslagen	-	Bm	
10	moraine from Stekenjokk	-	Sm	
11	high humified peat	-	hp	packed with 50kPa
12	low humified peat	-	lp	

The bentonite used was sodium-treated calcium bentonite and it was applied at two levels, 5 and 10 % by weight (see Table 1). Apart from normal quarry sand (samples 1,2) mine waste sand of various types was also tested.

Sample 3, "svartmocka", was an undisturbed sample of sediment which had settled out from mine rinsing water.

A coarse grained, unweathered mine sand was tested alone (sample 5) and with the inclusion of 10% bentonite (sample 6). A weathered sample of the same coarse sand with 10% bentonite (sample 7) was included to test whether the presence of soluble compounds in fresh mine sand reduces the effect of the bentonite. Finely grained waste sand was also included in the investigations (sample 8).

Moraine is intended as a stabilizing cover above the barrier layer (see Fig. 1) and two moraine types (samples 9,10) were tested for possible air/water barrier ability which would further protect and strengthen the barrier construction.

Finally, peat at two degrees of humification (samples 11,12) was included for analysis.

The symbols given to the samples in Table 1 are used in tables and figures throughout this report.

Before analyses were carried out, samples of the 12 materials were transferred to special standard steel cylinders with dimensions 5 cm height, 7.2 cm inner diameter and 203.6 cm^3 volume. These cylinders are in routine use at the Division of Hydrotechnics and are designed to fit in all equipment used for measuring physical parameters.

Packing of samples was carried out in an oedometer designed and described by Persson (1984). Six replicates of each material were prepared by packing to achieve a particular dry bulk density (Table 1). However, a pre-condition for subsequent physical tests on cylinders is that they are exactly full. It was found that the samples containing bentonite could not be compressed sufficiently to fit in the cylinder at the desired dry bulk density levels shown in Table 1. Actual bulk density values obtained by packing are shown in Table 2. Undisturbed materials (samples 3,4) were cut to fit into cylinders without packing.

METHODS

The following physical parameters were determined on all samples:

particle size distribution

moisture retention curves

total porosity (E) and air-filled porosity (E_g)

dry bulk density (γ_t)

density of solids (ρ_s)

diffusion coefficient at different tension steps (D)

air permeability coefficient at different tension steps (K_a)

Particle size distribution was determined by wet-sieving and sedimentation methods of mechanical analysis in routine use in the Division of Hydrotechnics (Ljung, 1987).

Dry bulk density (γ_t) was calculated from $\gamma_t = W_s/V_t$, where W_s is the total weight of the dry sample and V_t is the volume of the sample.

Density of solids (ρ_s) was measured by addition of a measured volume of 96% alcohol (v) to a known weight of dry material (a) in a 50 ml flask. Then $\rho_s = a/50-v$.

Total porosity (E) was calculated from values obtained above such that $E = 1 - \gamma_t/\rho_s$, cm^3/cm^3. The gas-filled porosity (E_g) is the difference between total porosity and volumetric water content (E_w) at any tension step.

Moisture retention curves show water content of the material after a range of increasing tension steps. Samples were first saturated from below, then set on porous ceramic plates with matric tension applied from below. The following tensions were applied in sequence: 0.05, 0.15, 0.30, 0.50, 1.00 and 6.00 m water column (mwc). Tensions up to and including 0.50 mwc were created by a suspended column of water, those above by vacuum pump. Moisture content at 150.0 mwc was determined on a small sample of disturbed material. When equilibrium was attained at each tension, samples were weighed and transferred to apparatus for determining D and K_a. When all analyses were carried out at all tension steps, samples were dried at 105° C for 72 hours.

Diffusion coefficient was determined in an apparatus described by Edling (1986) which uses a non-steady state principle. The sample in its cylinder was connected to the apparatus as shown in Fig. 2. The apparatus consists of a battery of twelve such units in which twelve samples can be tested simultaneously. When all samples were connected in series to the N_2-gas tube, all clamps were opened and nitrogen was allowed to circulate through the system for 2 minutes. All clamps were then closed, isolating the sample and the chamber above and timing began (T_0). After 10 min. stabilization time, sampling began at unit 1. A 50 μl sample was taken from the chamber using a Hamilton gas-tight syringe and injected into a gas chromatograph (Hewlett Packard 5880A) with a Molecular Sieve 13A and a Poropac Q column. Results of analyses showed relative concentration of oxygen and nitrogen gas in the sample (total 100%).

Three replicate gas samples were taken from each chamber in sequence and time of sampling noted in each case (T_1, s). Nitrogen concentration in the chamber at this first measurement (N_1) usually lies around 99.5%.

When all N_1,T_1 values have been obtained, a time interval is left in which diffusion occurs between the bottom of the sample which is in contact with the atmosphere and the top of the sample which is in contact with the nitrogen-filled chamber. Length of this time interval depends on how long it takes for a measurable amount of nitrogen to diffuse from the chamber. In the very impermeable materials tested in this experiment, this time interval was up to 48 hours. To prevent samples drying out from their lower surface during this period, samples were transferred to a semi-enclosed container. Sampling was then repeated to determine the new nitrogen concentration in chambers (N_2) at this second sampling time (T_2).

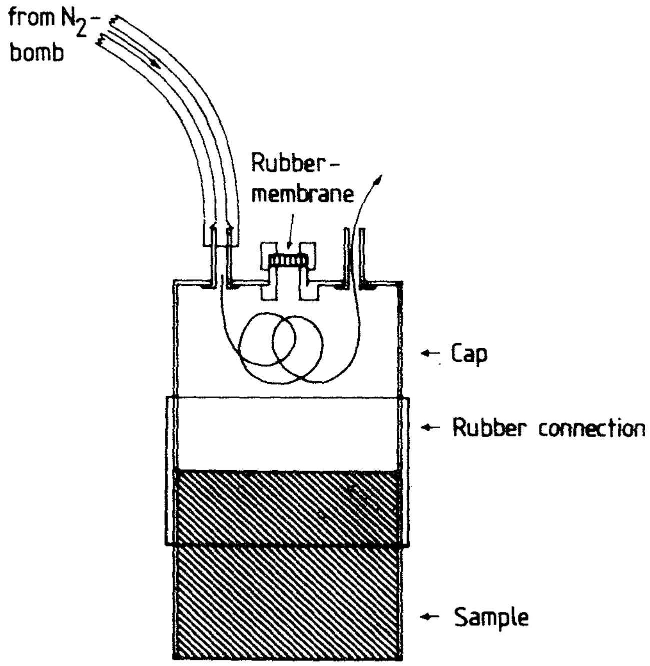

Fig. 2. Diagram of individual unit of apparatus for measuring non-steady state diffusion
Principskiss över apparat för mätning av icke-stationär diffusion

The diffusion coefficient (D_1) is calculated from results obtained with the expression:

$$D_1 = (l_s \cdot l_c/T_2 - T_1)\ (2.303 \log N_1 - N_a/N_2 - N_a)$$

where:

D_1 = uncorrected diffusion coefficient, cm^2/s
l_s = length of sample, here 5 cm
l_c = length of chamber, "
T_1, T_2 = sampling times 1 and 2, seconds after T_0
N_1, N_2 = nitrogen concentrations (%) at T_1, T_2
N_a = nitrogen concentration in the atmosphere, approx. 78%

A correction factor (y) for this apparatus must be applied to the D_1 value obtained to give the true diffusion coefficient D:

$$D = D_1 \cdot y$$

where $y = 1 + 0.34(E_g)(l_s/l_c)$, E_g = air-filled porosity, other terms as above.

After diffusion was measured, samples were transferred to an apparatus for determination of air permeability coefficients (K_a) as described by Edling (1986). Samples are connected to the apparatus as shown in Fig. 3. A PVC tube connects the sample to the water jar (c). When tap (d) is opened, water runs out and creates a vacuum over the water in the jar, causing air to be drawn in through the sample. At equilibrium at any pressure gradient, the volume of water leaving via the tap is equal to the volume of air being drawn in through the sample. By measuring the pressure gradient and the volume of water collected during a two minute period, K_a values can be obtained from $q = K_a \cdot A \cdot dP/l \cdot t$, where:

q = measured volume of water collected, ml
K_a = air permeability coefficient
A = cross-sectional area of sample, cm^2
dP = pressure gradient, cm water column
l = length of sample, cm
t = time, min.

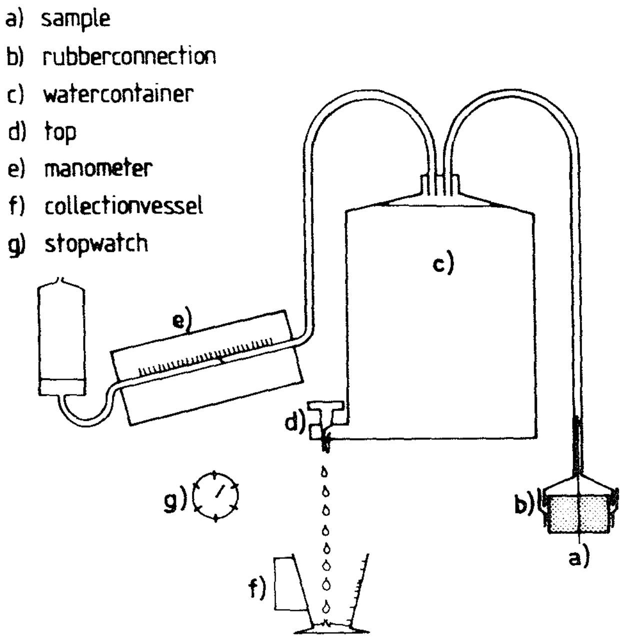

Fig.3. Diagram of apparatus for determining air permeability coefficient
Principskiss över luftgenomsläpplighetsapparat

Statistical analysis

The arithmetic mean and the coefficient of variation was calculated from the six replicates of each material. The relationship between diffusivity and air-filled porosity was analysed statistically for each material. Both linear and non-linear equations were fitted. Non-linear models were fitted by the least squares technique using the SAS procedure NLIN (SAS Institute Inc., 1982).

The relationship between diffusivity and air-filled porosity has been found to have form $D/D_o = C\,E_g^a$, where C and a are constants for a particular material (Currie, 1960). Two parameters were therefore employed in non-linear regression analysis.

It has been suggested that the nature of the relationship between D/D_o and E_g is linear, of form $D/D_o = a(E_g - b)$ where a,b are constants, when the range of E_g values is very low. (Bakker & Hidding, 1970). The best fit line for the data on each material was selected on the basis of best R^2 value.

RESULTS

Particle size distribution

Results of mechanical analysis of the different materials (with the exception of peat) are shown in Table 2 and Fig. 4 where particle size classes are according to the Atterberg classification system. In general, materials were well sorted with 70% by weight of particles falling into 1-3 adjacent particle size classes. This allows materials to be ranged in order of particle size, decreasing particle size in the case of Table 2.

Table 2. Mechanical composition of the materials used (excl.peat), % by weight in Atterberg size classes
Mekanisk sammansättning av de undersökta materialen (exkl.torv). Viktprocent av respektiva kornstorleksklasser

Material	% by weight of fraction						
	clay	f.silt	c.silt	v.f.sand	f.sand	med.sand	c.sand
95s/5b	7	2	5	9	8	(40	29)
90s/10b	11	2	6	8	(9	37	27)
Sm	3	3	7	(18	29	20	20)
Bm	2	2	12	(19	29	20)	15
90wws/10b	11	2	6	(31	33	10)	7
cws	12	4	(18	31	30)	5	0
90cws/10b	18	5	(16	26	30)	5	0
fws	8	(15	39	35)	3	0	0
svm	14	(19	37	23)	6	1	0
tsl	(72)	8	6	11	2	1	0

( ) = includes 70 wt.% of material

The order in which samples are listed in Table 2 follows the same pattern as that in which samples occur from right to left in Fig. 4., which shows particle size distribution curves summarized in a single diagram. Thus the coarsest material is 95% sand/5% bentonite and the finest is the unstructured clay (tsl) with 70% clay. Note that the "svartmocka" sample (svm) is, on the basis of its mechanical composition, a silt with a high organic matter content.

More complete particle size distribution curves are contained in an appendix to this report (Appendix 1, Figs 1-10).

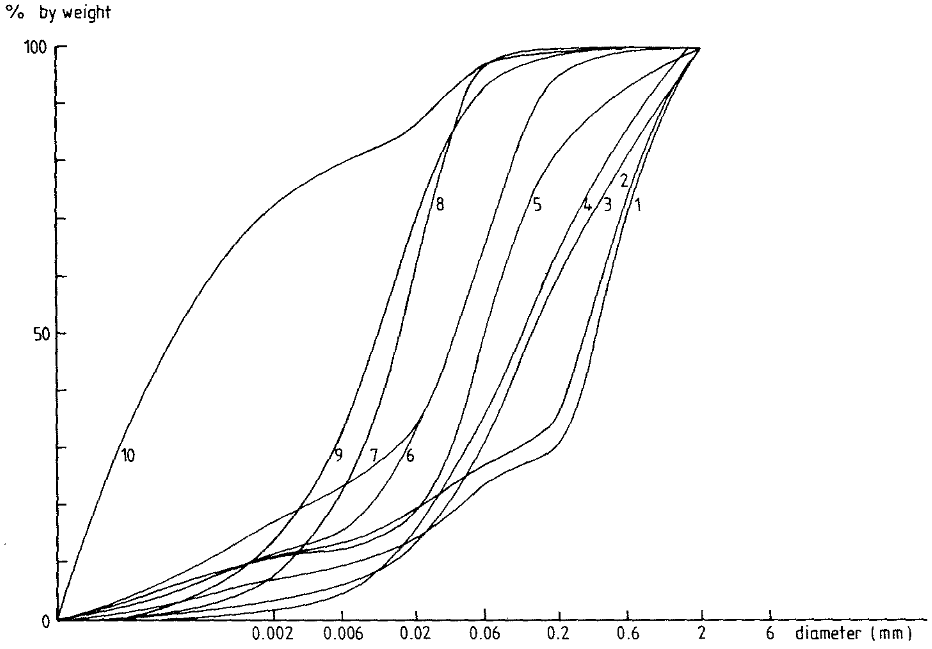

Fig. 4. Summary of particle size distribution curves
Sammanfattning av kornstorleksfördelningskurvor
1 = 95s/5b, 2 = 90s/10b, 3 = Sm, 4 = Bm, 5 = 90wws/10b, 6 = cws, 7 = 90cws/10b, 8 = fws, 9 = svm, 10 = tsl, (11 = hp, 12 = lp).

All results reported later in this section are quoted with samples in the order given in Table 2, of decreasing particle size.

Note that in tests on moraine materials, larger pebbles and stones which were present in the original material could not be included in standard cylinders are were thus not included in mechanical analysis.

Physical parameters

Table 3 summarizes some physical parameters of the materials tested. Each value in Table 3 is a mean of six replicates.

The lower than desired dry bulk density values shown in Table 3 have been discussed earlier, in the Methods section of this report (compare Tables 1 and 3).

In most mineral soils, density of solids lies between 2.6 and 2.7 g/cm^3. From Table 3 it can be seen that mine waste sands of all types (weathered or fresh, coarse or fine grained) have considerably higher densities of solids. Values lie between 2.9 and 3.1 g/cm^3 and are a reflection of the presence of metal oxides and heavy metals (Hillel, 1980).

Table 3. Summary of some physical data, symbols for materials as in Table 1
Sammanfattning av några fysikaliska egenskaper, förkortningar enl. tabell 1

Material	total porosity vol.%	moisture content at 150 mwc vol.%	dry bulk density g/cm^3	density of solids g/cm^3
95s/5b	33.4	12.2	1.80	2.70
90s/10b	36.3	17.3	1.71	2.69
Sm	26.8	4.1	1.99	2.72
Bm	26.8	2.9	1.96	2.68
90wws/10b	44.4	18.9	1.66	2.99
cws	35.9	9.8	1.94	3.02
90cws/10b	45.1	19.3	1.68	2.99
fws	47.4	18.6	1.60	3.04
svm	71.1	14.0	1.20	2.63
tsl	55.0	38.6	1.56	2.67
hp	90.0	19.6	0.27	1.55
lp	92.3	17.6	0.22	1.55

Moisture content at 150 m water column shows how effectively the materials or mixtures can retain water at very high tension. It can be seen from the values obtained that inclusion of bentonite greatly increased the moisture holding ability of the coarser materials.

Diffusion through materials

Table 4 shows a summary of results from diffusion coefficient determinations. In this investigation, there were 12 different materials, 5 different matric tension steps, 6 replicate cylinders per material and 3 replicate measurements of (N_1,T_1), (N_2,T_2) per cylinder. To report results, averages were taken at several stages. The three replicate measurements of N content per cylinder were combined to give an average diffusion coefficient (D, cm^2/s) value per cylinder and tension step. Results from all 6 replicates were averaged, but since there was wide variance between replicates in many cases, all D-values obtained are included in an appendix to this report (Appendix 2, Tables 1 - 12). Means and coefficients of variation are included at the foot of these tables.

It is customary to relate diffusion of a gas through a material to diffusion of the same gas through air. This relationship is known as diffusivity (D/D_o) and is obtained by dividing the corrected diffusion coefficient (D) with the diffusion coefficient of the diffusing gas in experiments through air (D_o). In the apparatus used in this investigation, the diffusing gas was nitrogen which has D_o = 0.201 cm^2/s at the ambient laboratory temperature of 20° C (Armstrong, 1979).

Table 4 shows results from diffusion experiments summarised as diffusivity values. The values shown include the mean of six replicates per material and the maximum and minimum values obtained at four tension steps. Results of D and D/D_o for all replicates and all tension steps are given in Appendix 2. To facilitate comparisons between results for different materials, values have been rounded off to the nearest integer and raised to the power of 10^{-5}.

There was a wide variation between replicates (see Appendix 2), to a power of 10 in some cases. Such variations would seem to be due to differences in packing and perhaps incidence of blocked pores. There may also be some experimental error in handling of cylinders. However, the three replicate N_1 and N_2 measurements, of which every D-value is an average, varied only by less than 0.1 % so this could not be regarded as a source of variation.

Air content of materials

Table 5 gives a summary of air-filled porosity values (vol.%) at the various tension steps. These values have been rounded off to the nearest integer and maximum and minimum values obtained are given together with the mean of the six replicates for each material.

Results shown in Table 5 are an indirect indication of the moisture holding capacity of the material at the various tension steps. Values for total porosity have been given earlier, in Table 3.

Table 4. Summary of diffusivity values, D/D_o x 10^{-5}
Sammanfattning av diffusivitetsvärden, D/D_o x 10^{-5}

Material	matric tension, m water column							
	0.15		0.50		1.00		6.00	
	x	(max-min)	x	(max-min)	x	(max-min)	x	(max-min)
95s/5b	15	(22-8)	17	(25-6)	42	(58-24)	92	(154-48)
90s/10b	20	(32-3)	18	(30-11)	25	(55-6)	112	(135-86)
Sm	10	(15-4)	11	(15-6)	31	(54-22)	3270	(3880-2130)
Bm	15	(29-7)	22	(36-12)	169	(278-75)	2910	(3260-2480)
90wws/10b	21	(37-7)	9	(18-3)	12	(24-1)	44	(73-15)
cws	5	(8-3)	19	(25-10)	41	(89-9)	352	(437-296)
90cws/10b	6	(11-4)	28	(36-6)	53	(90-28)	1490	(2000-470)
fws	4	(6-3)	4	(8-1)	45	(103-8)	56	(69-45)
svm	2	(3-1)	13	(20-6)	488	(520-466)	412	(863-70)
tsl	1	(3-1)	3	(5-1)	2	(3-2)	3	(5-1)
hp	19	(47-5)	16	(40-5)	1110	(1980-530)	1950	(2430-1420)
lp	9	(17-4)	23	(46-7)	535	(950-129)	4900	(6790-2490)

Table 5. Summary of air-filled porosity measurements, vol.%
Sammanfattning av luftfyllda porositeten (vol.%)

Material	matric tension, m water column							
	0.15		0.50		1.00		6.00	
	x	max-min	x	max-min	x	max-min	x	max-min
95s/5b	3	(4-1)	5	(6-4)	6	(7-5)	10	(12-9)
90s/10b	1	(2-1)	3	(4-2)	4	(4-3)	6	(8-5)
Sm	2	(3-2)	4	(5-3)	5	(6-5)	15	(16-14)
Bm	1	(2-0)	3	(4-2)	4	(6-3)	18	(20-16)
90wws/10b	2	(3-1)	2	(4-2)	2	(4-2)	10	(10)
cws	2	(5-1)	2	(5-1)	3	(6-1)		(10-5)
90cws/10b	2	(3-1)	4	(6-2)	5	(7-4)	8	(10-7)
fws	1	(1-0)	7	(7-6)	8	(9-6)	10	(11-8)
svm	1	(2-0)	6	(7-5)	9	(12-7)	15	(18-13)
tsl	2	(2-1)	2	(3-1)	3	(4-2)	7	(8-6)
hp	4	(5-3)	7	(9-5)	16	(17-15)	33	(35-31)
lp	5	(6-3)	8	(13-5)	19	(22-16)	43	(47-41)

Complete moisture content and air-filled porosity values for each individual cylinder are given in Appendix 2, Tables 1-12.

All values of diffusivity and air-filled porosity from Tables 4 and 5 and from Appendix 2 have been used to plot the points shown in Figs. 5 to 16. These show diffusivity as a function of air -filled porosity, at the tension steps used in this experiment. D/D_0 is given on the logarithmic vertical axis, E_g on the linear axis and tension steps are distinguished by a range of symbols within each graph.

Statistical analysis of the relationship between diffusivity and air-filled porosity was unsatisfactory in the case of the more impermeable materials, especially the clay (tsl), because of the very narrow range of E_g values obtained. The best fit equations for those materials where a reasonably good regression coefficient was obtained ($R^2 > 0.5$) are shown in Table 6.

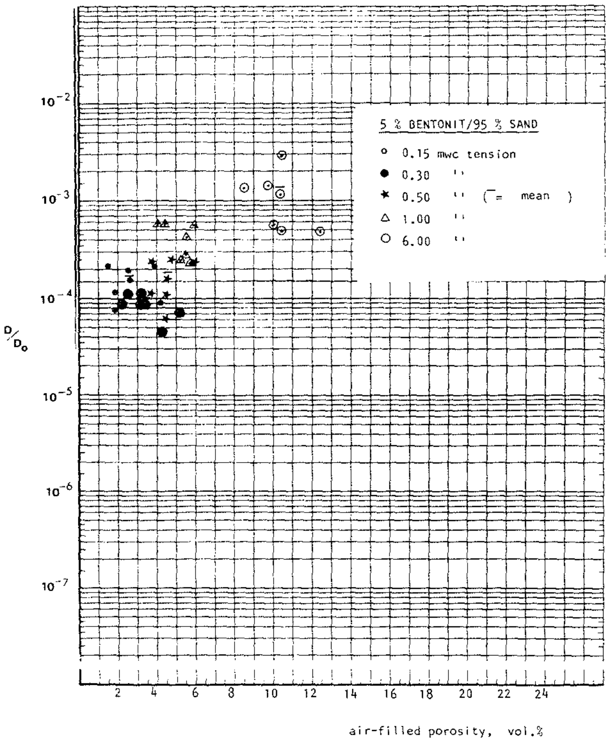

Fig. 1. Diffusivity (D/D_o) as a function of air-filled porosity (vol-%). 95s/5b.

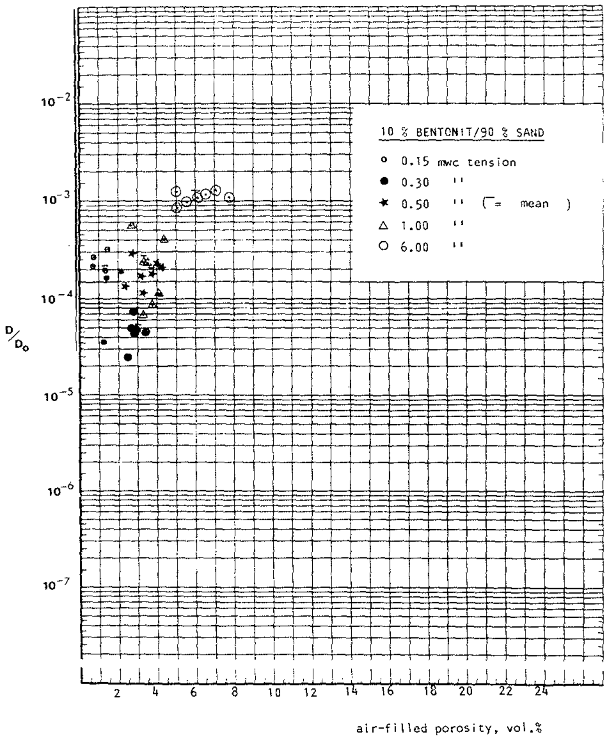

Fig. 2. Diffusivity (D/D_o) as a function of air-filled porosity (vol-%). 90s/10b.

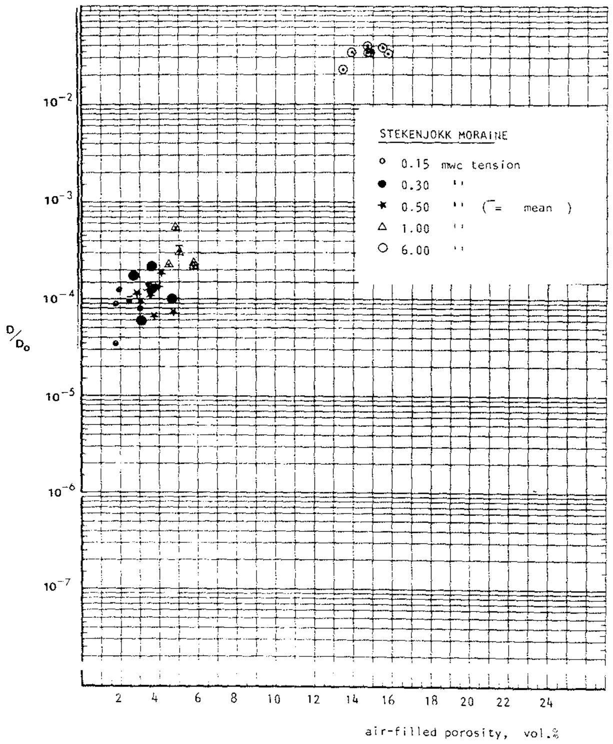

Fig. 3. Diffusivity (D/D_o) as a function of air-filled porosity (vol-%). Sm.

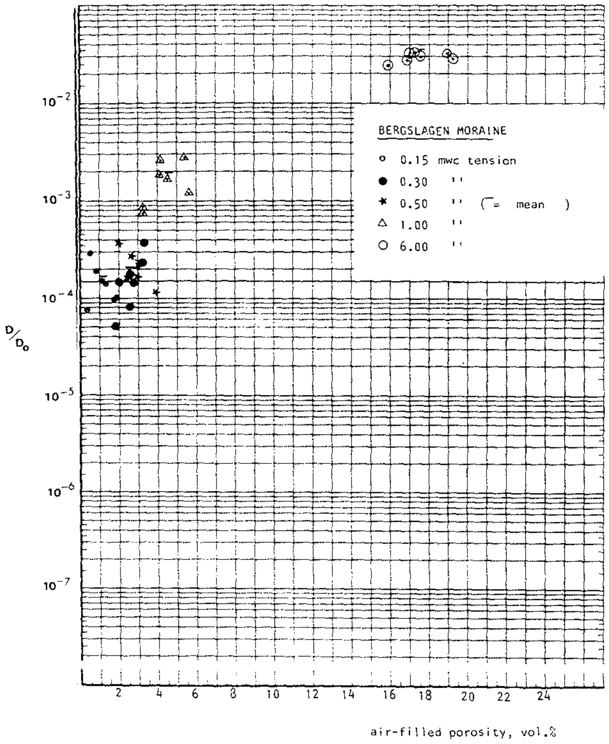

Fig. 4. Diffusivity (D/D_o) as a function of air-filled porosity (vol-%). Bm.

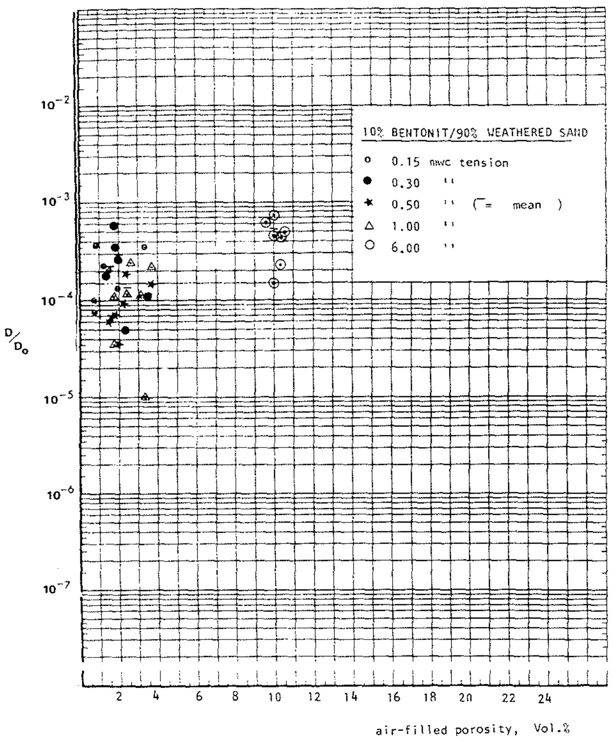

Fig. 5. Diffusivity (D/D_o) as a function of air-filled porosity (vol-%). 90wws/ob.

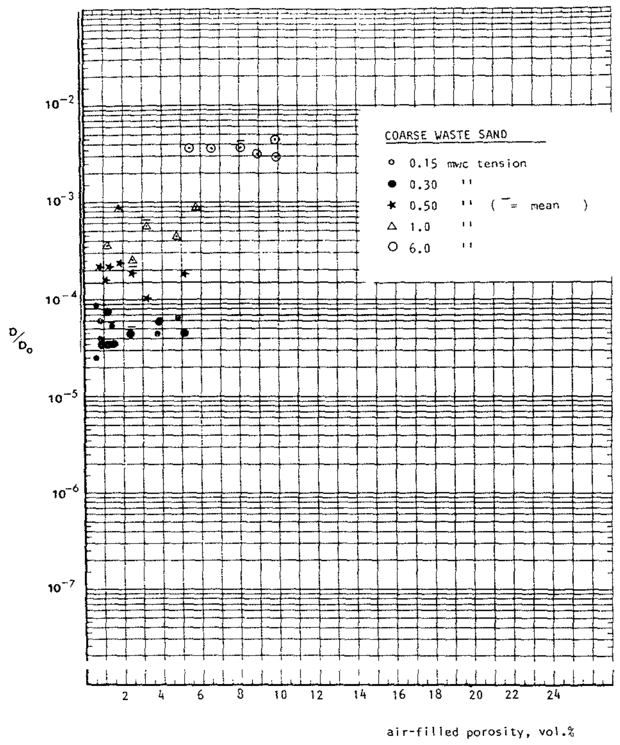

Fig. 6. Diffusivity (D/D_o) as a function of air-filled porosity (vol-%). cws.

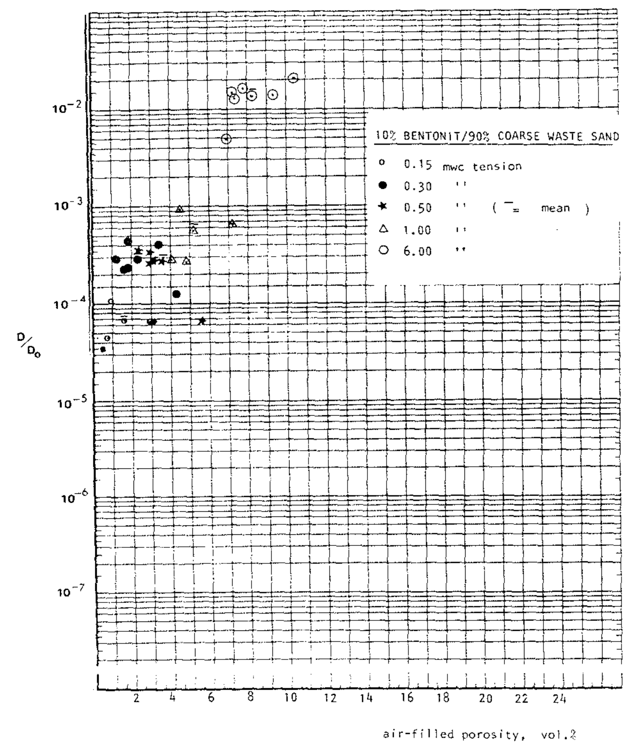

Fig. 7. Diffusivity (D/D_o) as a function of air-filled porosity (vol-%). 90cws/10b.

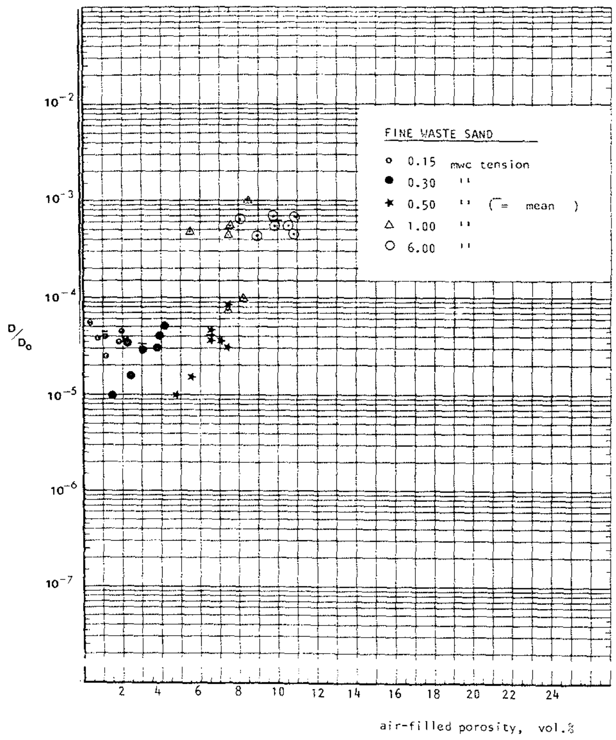

Fig. 8. Diffusivity (D/D_o) as a function of air-filled porosity (vol-%). fws.

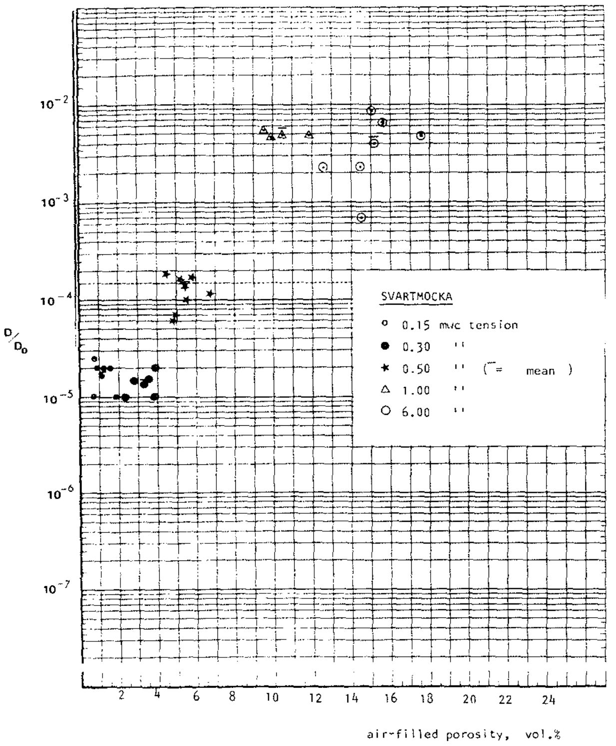

Fig. 9. Diffusivity (D/D_o) as a function of air-filled porosity (vol-%). swm.

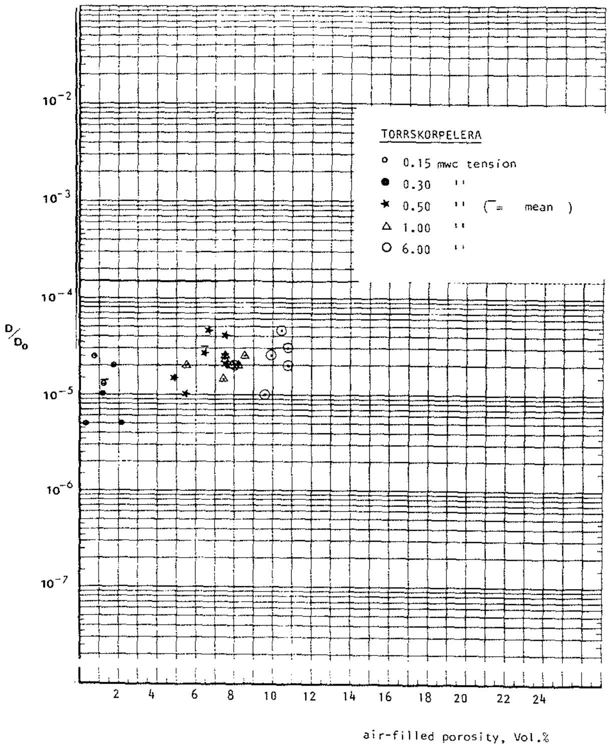

Fig. 10. Diffusivity (D/D_o) as a function of air-filled porosity (vol-%). tsl.

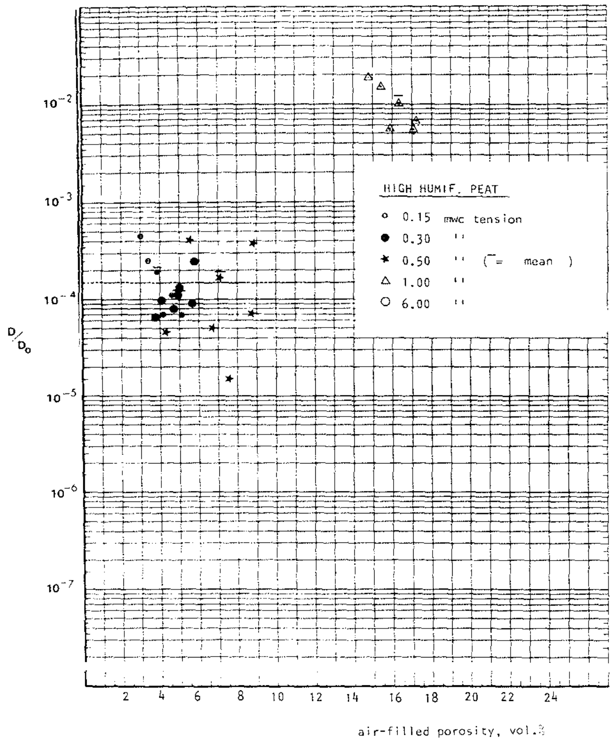

Fig. 11. Diffusivity (D/D_o) as a function of air-filled porosity (vol-%). hp.

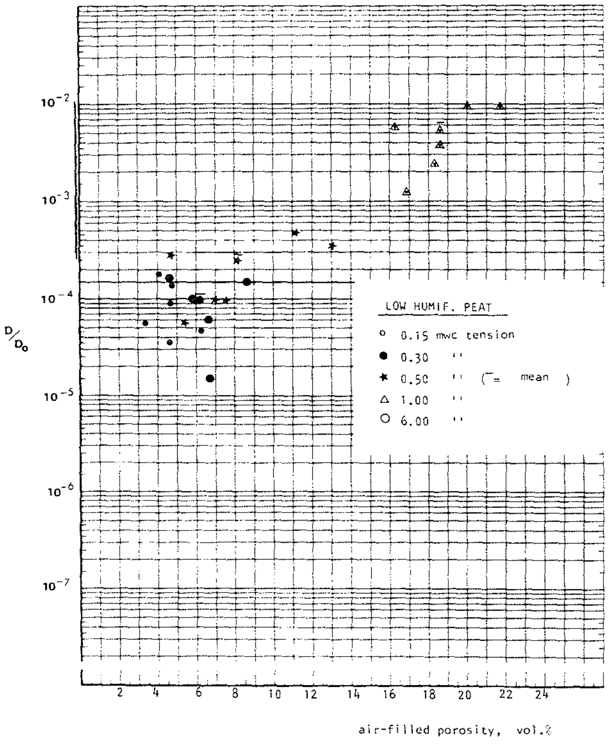

Fig. 12. Diffusivity (D/D_o) as a function of air-filled porosity (vol-%). lp.

Table 6. Relationship between diffusivity and air-filled porosity
Sambandet mellan diffusivitet och lufthalt

Material	Range of E_g	Equation, $D/D_o = f(E_g)$	R^2
moraine	(0.01-0.2)	$D/D_o = 0.7\ E_g^{1.8}$	0.98
high H peat	(0.03-0.35)	$D/D_o = 0.1\ E_g^{1.4}$	0.81
low H peat	(0.03-0.47)	$D/D_o = 0.8\ E_g^{3.3}$	0.95
silt (svm)	(0.01-0.18)	$D/D_o = 0.1\ E_g^{1.6}$	0.62
sand + 10ben	(0.01-0.08)	$D/D_o = 0.02(E_g - 0.01)$	0.62
cws	(0.01-0.10)	$D/D_o = 0.04(E_g - 0.01)$	0.62
cws + 10ben	(0.01-0.10)	$D/D_o = 0.2(E_g - 0.02)$	0.67

As suggested in the literature and discussed earlier in this report, the relationship between diffusivity and air-filled porosity is best described by a linear equation when the range of E_g values is narrow. For extremely narrow E_g ranges, it was impossible to fit a line to the cluster of points.

The regression coefficient as shown in Table 6 is mainly an indication of the spread of E_g values employed. For the most permeable materials (peat, moraine) the regression coefficient was 0.8 to 0.9, whereas for the more impermeable materials it was lower than 0.4. The equations given in Table 6 are shown graphically in Appendix 3, Figs. 1-7.

Moisture retention in materials

A summary of moisture-holding ability of materials is given by Fig. 17, in which moisture characteristics for all 12 materials have been plotted onto a single set of axes. Curves show moisture content (vol.%) as a function of matric tension (mwc). Total porosity is also indicated as the x-axis intercept. More complete, individual diagrams for each material are given in Appendix 4, Figs. 1-12.

A comparison of Fig. 4 and 17 shows that the moisture characteristic for a material is determined by particle size or, indirectly, pore size. Curves 1-12 in Fig. 17 follow the same order as those arranged according to particle size in Fig. 4., with the exception of the moraines and the svartmocka sample.

It can be seen from Fig. 17 that curve 10 (torrskorpelera) best retains water at increasing tension and is thus likely to be the best barrier material.

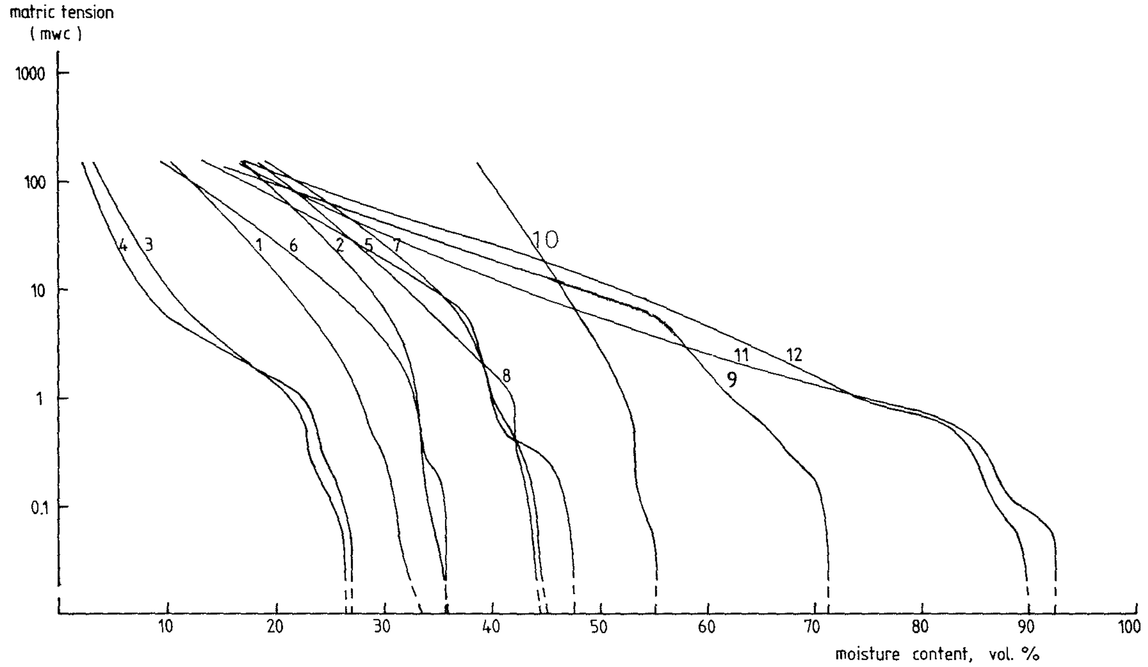

Fig. 17. Moisture-holding ability of materials.
Vattenbindningsförmåga hos de olika material.
1 = 95s/5b, 2 = 90s/10b, 3 = Sm, 4 = Bm, 5 = 90wws/10b, 6 = cws, 7 = 90cws/10b, 8 = fws, 9 = svm, 10 = tsl, 11 = hp, 12 = lp.

Air permeability

Air permeability coefficients (K_a, cm/min) are summarized in Table 6.

Since very impermeable, unstructured materials were the subject of this experiment, few results were obtained for K_a, especially at the lower matric tensions (less than 0.50 mwc). In each individual measurement on cylinders, the gradient applied in the apparatus (see Fig. 3) could not be allowed to exceed the matric tension at which the sample had previously been drained. The lowest possible value which can be measured in this apparatus was shown to be 0.01 cm/min.

Results obtained for K_a are difficult to present graphically since they cover such a small range even at the full range of matric tension employed in this experiment. An attempt to portray K_a as a function of air-filled porosity for the least permeable materials is shown in Fig. 18.

At a reference value of 5 vol.% air Fig. 18), air permeability coefficient was 4.4 cm/min for the fresh coarse mine sand + bentonite mixture. 1.3 for moraine and 0.00 for all other materials. Air permeability was in general much higher in the fresh coarse mine sand + bentonite sample than in any of the others. This indicates that the barrier properties of the bentonite are, in fact, adversely affected by soluble compounds in fresh mine wastes (see Materials section).

Table 7. Air permeability coefficient, K_a (cm/min)
Luftgenomsläpplighetskoefficienter, K_a (cm/min)

Material	matric tension, m water column		
	0.50	1.00	6.00
95s/5b	0.00	0.00	0.60
90s/10b	0.00	0.00	0.10
Sm	0.13	1.30	3.82
Bm	0.10	2.10	1.40
90wws/10b	0.00	0.02	0.04
cws	0.10	-	0.30
90cws/10b	(8.5)	4.40	-
fws	0.10	0.01	0.62
svm	0.00	0.17	0.34
tsl	0.00	0.01	0.01
hp	1.60	1.60	21.10
lp	0.30	1.10	12.00

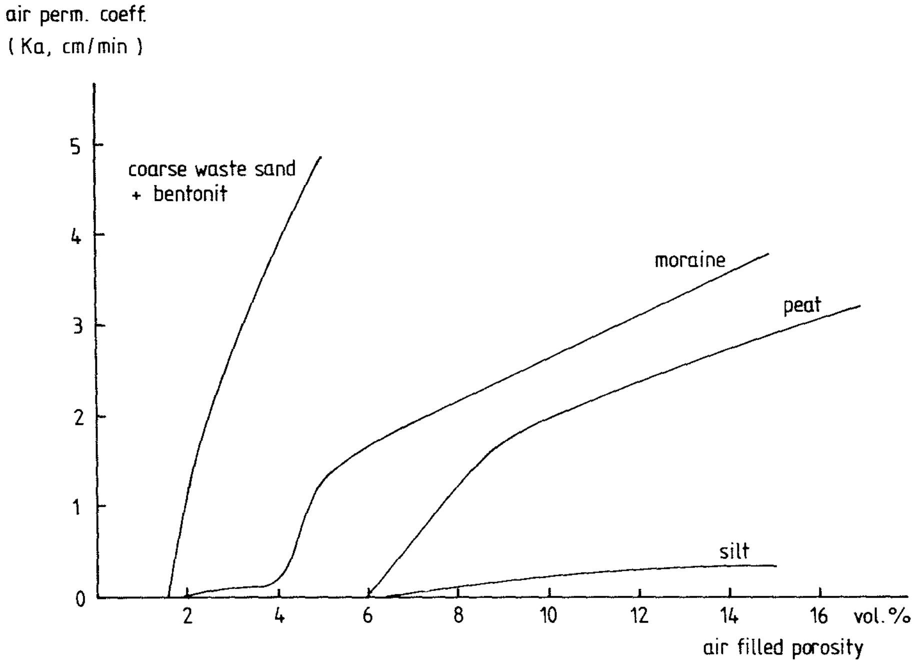

Fig. 18. Air permeability coefficient (K_a, cm/min) as a function of air-filled porosity (E_g, vol.%)
Luftgenomsläpplighet (cm/min) som funktion av lufthalt (vol.%)

DISCUSSION

The discussion deals with the two aspects of this investigation mentioned in the Introduction, namely (i) the effectiveness of materials as barriers to air and water movement and (ii) the accuracy of the methods employed at very low air-filled porosity values.

1. Barrier properties of materials

From the diagram of a proposed barrier construction (Fig. 1), it can be seen that the actual barrier layer lies at a depth of over 2 metres below the surface. It is overlain by topsoil, a stabilizing layer of moraine and a drainage layer. It is thus unlikely to be exposed to changes in pressure gradient and movement of air by convection is not likely to occur. The air permeability coefficients (K_a) obtained in this investigation will thus not be applicable directely. However, they can be taken as an indication of the permeability of the material to water, (Eriksson, 1982).

Theoretically, diffusivity (D/D_0) of an unstructured material is a function of air-filled porosity, tortuosity of pores and frequency of blocked pores within the material. It is thus determined chiefly by the moisture retaining ability of the material which in turn is determined by particle size (Figs. 4, 17). Particle shape is of less importance in wet materials since water films round off particles and reduce the influence of their shape (Currie, 1961).

A summary of both diffusivity and air-filled porosity values (Tables 4, 5) shows that the unstructured clay was the most effective barrier material. It remains almost fully saturated at tensions of up to 6.0 m water column and diffusion coefficients are very low at all tension steps.

Some of the other materials retained water equally well up to 1.0 m wc. Coarse mine sand, weathered mine sand + bentonite, quarry sand + 10 % bentonite have, for example, an identical air-filled porosity to the clay (3 vol.%) at 1.0 mwc. However, when diffusivity values are compared, there are large differences between the clay and the other three materials and only weathered mine sand + bentonite has equally low diffusivity.

A comparison of result (Tables 4, 7) from the three materials based on coarse mine waste (weathered + bentonite, unweathered, unweathered + bentonite) shows that as suspected, leachable compounds in fresh mine sand adversely affect the sealing properties of bentonite. This is not just an effect of packing or the low dry bulk density obtained in samples containing bentonite (Table 3). Weathered waste sand + bentonite and unweathered waste sand + bentonite have identical dry bulk density values and very similar moisture retention curves (Curves 5, 7 in Fig. 17). Yet diffusivity in the unweathered + bentonite is 3 times higher at 0.5 mwc, 4 times at 1.0 mwc and 30 times higher at 6.0 mwc. A glance at air permeability coefficients (Fig. 18) shows a similar trend occuring there.

Inclusion of 5 as opposed to 10 % by weight bentonite with sand does not give any great differences in either diffusion coefficients (Table 4,

Fig. 5) or moisture retention (Table 5, Fig. 17). However, in preparation of these samples for this investigation, the bentonite was thoroughly mixed with the sand before wetting. In practice, it is proposed to rotavate bentonite into the sand in the field. Such a mixture would be expected to be less homogenous and it would be necessary to repeat analyses on undisturbed samples taken in the field before any conclusions can be drawn on the barrier properties of bentonite/sand mixtures.

All of the material proposed for the barrier layer (Nos. 1 - 8, Table 1) are adequate at the lower matric tensions (< 1.0 mwc). The silt (svm) becomes unstable at 1.0 mwc and the weathered sand at 6.0 mwp (Table 4). The clay is, as mentioned previously, very effective at all the tensions measured.

The peat samples investigated had poor barrier properties at tensions above 0.5 mwc. They have also a very high total porosity and are thus prone to compaction on drainage or loading.

Moraine is intended as a stabilizing cover for the entire barrier layer construction (Fig. 1). It is to be laid as a 1.5 m thick deposit over a drainage layer and an approximately 0.5 m thick barrier layer. In field conditions, the drainage layer will function as a perched watertable and the moraine will be subjected to a matric tension of 1.5 mwc at its upper surface (and 0.0 mwc at its lower surface). A check of results (Table 4) shows that between 0.5 and 1.0 mwc, diffusivity in the moraines is between 1.1 and 169 x 10^{-5}. Fig. 18 shows the permeability of the moraines at these tensions. In field conditions, moraine material is likely to be more permeable than the samples tested if larger stones and boulders are included. Cracks and fissures are likely to originate at the interface of larger stones and the finer sandy material.

In conclusion, laboratory investigations shows a range of air and water barrier abilities in the materials tested and allow some recommendations to be made on choice of materials for field trials. It must be remembered, however, that tests were carried out on small, carefully packed and uniform samples and results of additional trials in actual constructions would be necessary before firm recommendations could be made.

2. Evaluation of method

The non-steady state method used to measure diffusion coefficient was found to be capable of giving results even at very low air-filled porosities.

Very low diffusion coefficients were obtained in many cases during this investigation. It is interesting to compare diffusion in saturated samples to diffusion through pure water. The diffusing gas in the apparatus was nitrogen (Fig. 2), which has a diffusion coefficient in pure water of 2.10 x 10^{-5} cm^2/s at 20^o C. Diffusivity through water $D_w/D_o = 2.10 \times 10^{-5}/0.210 = 10.45 \times 10^{-5}$ (data from Armstrong, 1979). This value can then be compared to diffusivity values for materials from Table 4.

Table 8 below shows the pattern obtained when diffusivity values obtained from samples intended as barrier materials (listed in order of decreasing particle size) are compared to diffusivity through water:

Table 8. D/D_0 (from Table 4) compared to D_w/D_0: the measured D/D_0 value is greater than (+), equal to (=) or less than (-) D_w/D_0
D/D_0 (jfr tabell 4): det uppmätta D/D_0-värdet är större än (+), lika med (=) eller mindre än (-) D_w/D_0

Material	matric tension, m water column			
	0.15	0.30	1.00	6.00
95s/5b	+	+	+	+
90s/10b	+	+	+	+
90wws/10b		-	+	+
cws	-	+	+	+
90cws/10b	-	+	+	+
fs	-	-	+	+
svm silt	-	+	+	+
tsl clay	-	-	-	-

A risk with the long time interval between measuring the first and second nitrogen concentration in the chamber (Fig. 2) is that of leakage from connecting tubes, ligatures, clamps or septa. Tests with a blind, solid cylinder showed that no leaks occurred in the apparatus or its components since no detectable nitrogen change occurred in the chamber in a period of 72 hours.

A problem arose with shrinking samples (peat) at higher matric tensions when the material pulled away from the cylinder walls. This was counteracted by inserting the lower end of the connecting rubber sleeve inside the cylinder and directly onto the surface of the sample.

The disadvantage with investigating very impermeable materials or materials at a very low range of air-filled porosity values is that the range of D/D_0 and E_g coordinates obtained is also very narrow. This means that statistical analyses of results are impossible in some instances and that regression coefficients tend to be low.

The linear equations obtained (Table 6) for 90 sand + 10 bentonite ($D/D_0 = 0.02(E_g - 0.01)$), coarse waste sand ($D/D_0 = 0.04(E_g - 0.01)$) and coarse waste sand + bentonite ($D/D_0 = 0.2(E_g - 0.02)$) agree well with results from Gradwell (1965) for clay loam with low air-filled porosity ($D/D_0 = 0.06(E_g - 0.02)$). The coefficients in the exponential equations obtained for moraine, peat and silt (Table 6) fall within the range reported by Glinski & Stepniewski (1983) from various sources.

There was a wide variation between replicates of the two main parameters measured, air content and diffusivity. Coefficients of variation are given in full in Tables 1 - 12, Appendix 2 and are summarized below in Table 9.

Table 9. Variation in measured air content (coefficient of variation, %)
Spridningen i uppmätt lufthalt (variationskoefficent, %)

Material	matric tension, m water column							
	Variation in air content				Variation in diffusivity			
	0.15	0.50	1.00	6.00	0.15	0.50	1.00	6.00
95s/5b	42	17	13	10	38	44	39	54
90s/10b	39	14	15	17	44	37	72	14
Sm	27	18	11	5	43	37	43	17
Bm	54	22	20	6	50	41	48	8
90wws/10b	64	33	26	3	55	59	70	46
cws	81	68	54	21	36	26	46	15
90cws/10b	69	32	21	15	42	39	49	34
fws	53	15	13	10	22	68	78	19
svm	34	13	18	10	35	34	5	66
tsl	33	32	16	10	61	54	14	48
hp	19	23	6	4	76	98	58	19
lp	21	37	10	5	63	67	60	29

As can be seen from the left hand side of Table 9, variation between replicates of air-content was greatest at the first matric tension step and decreased gradually with increasing matric tension. This indicates that the original variation is due to differences in packing, trapped air, edge effects etc. and differences decrease as samples settle and drain.

Variation in diffusivity values is not a function of variation in air-filled porosity, since the diffusion coefficient obtained in experiment (D_1) is corrected for the air content of the sample at the particular tension step (see METHODS). Error in measurement of nitrogen concentration was very small ($<$ 0.1 %) and, as mentioned previously, there were no leaks in the apparatus. Furthermore, when a particular cylinder was re-wetted and re-drained at a particular matric tension, the new diffusion coefficient obtained differed by less than 10 % from the first value obained. The variation between replicate cylinders was therefore presumably due to differences in packing, edge effects and irregularities in the sample material.

The method has been shown to be capable of measuring diffusion in very impermeable materials. It can therefore be applied in future investigations to measure gaseous diffusion through agricultural soils with very low air contents, for example puddled clays or compacted arable soils. It is hoped that future investigations will determine the lower limits of soil ventilation for growth.

SUMMARY

A number of materials were tested for their suitability as barriers to water and air movement. These materials are intended to form part of a layered cover for dumps of pyritic mine waste, to prevent pollution by oxidation and leaching.

A range of parameters were measured, including moisture retention in materials at increasing tension and diffusion, air permeability coefficients and particle size distribution of materials.

For the more permeable materials, the relationship between diffusivity and air-filled porosity was of the form $D/D_o = 0.1 \cdot E_g^{1.4}$ (peat) or $0.7 \cdot E_g^{1.8}$ (moraine). For the more impermeable materials, a linear equation was produced, of the form $D/D_o = 0.02(E_g - 0.01)$ (sand + bentonite).

Tests allowed the most suitable barrier materials to be identified and some recommendations to be made. However, the need for further investigations of materials in the field was established.

The investigation allowed the non-steady state method of measuring diffusion coefficient to be assessed at very low air contents which will be of interest in future work on agricultural soils.

SAMMANFATTNING

De här presenterade resultaten utgör ett led i undersökningen av luft- och vattenbarriäregenskaper hos några material aktuella för användning i ett täckskikt för gruvrestupplag. Materialen ska isolera upplagen mot regnvatten och mot luftens syre.

En rad fysikaliska parametrar bestämdes i laboratorieundersökningar, bl a vattenhållande förmåga, diffusions- och luftgenomsläpplighetskoefficienter och partikelstorleksfördelning hos materialen.

För de mest genomsläppliga materialen var sambandet mellan diffusivitet och lufthalt av typ $D/D_o = 0.1 \cdot E_g^{1.4}$ (torv) eller $= 0.7 \cdot E_g^{1.8}$ (morän). För de tätare materialen var sambandet linjärt, $D/D_o = 0.02(E_g - 0.01)$ (sand + bentonit).

Som följd av denna undersökning kunde de bästa materialen ur tätningssynpunkt identifieras. För att kunna göra mer detaljerade rekommendationer borde även fältundersökningarna på de aktuella materialen eller blandningarna också utföras.

Diffusionsmätningar på dessa täta material tillät en värdering av den icke-stationära metoden vid mycket låga lufthalter. Erfarenheter från denna tillämpning av metoden kommer att ligga till grund för framtida mätningar av diffusionskoefficient hos täta jordbruksmarker.

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APPENDIX 1

PARTICLE SIZE DISTRIBUTION OF MATERIALS

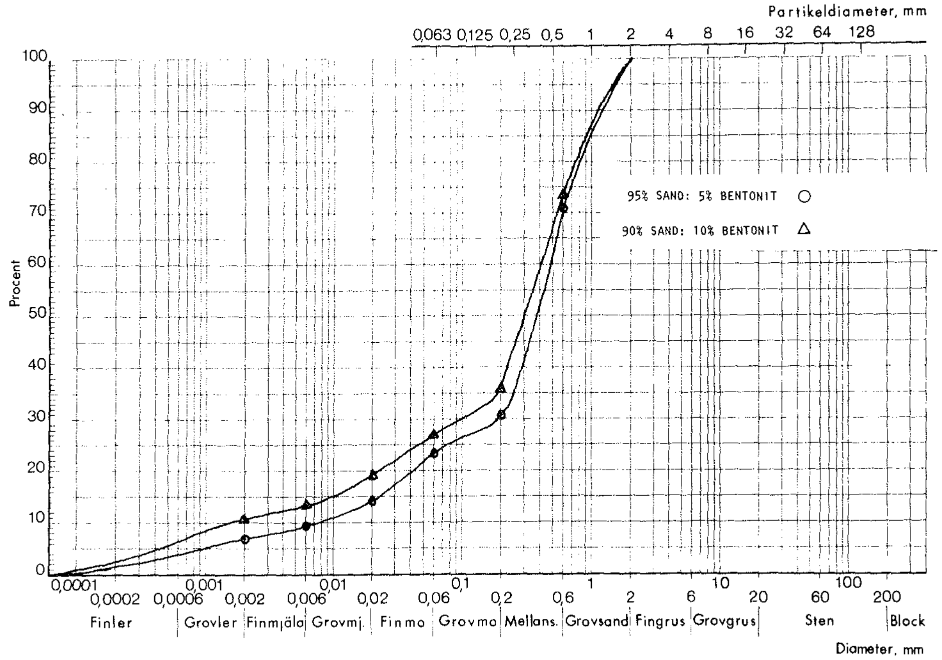


Fig. 1,2. Sand + bentonite mixtures

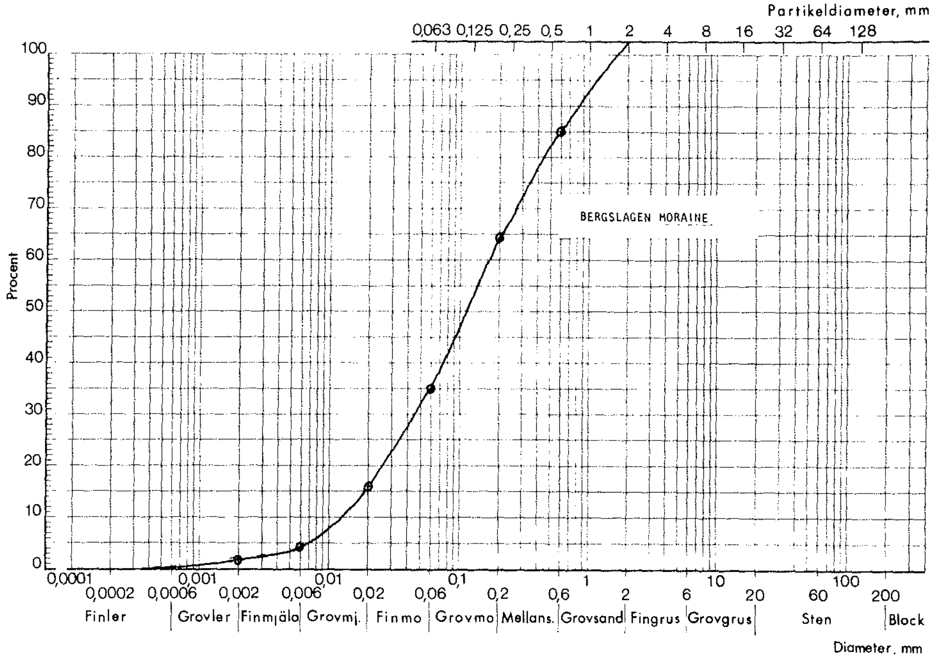
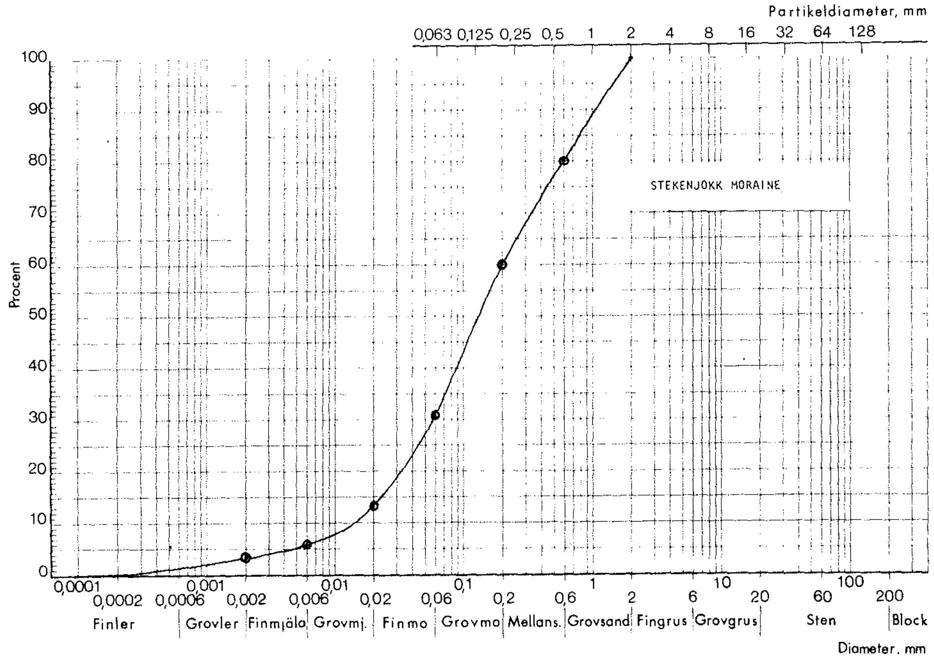


Fig. 3. Bergslagen moraine



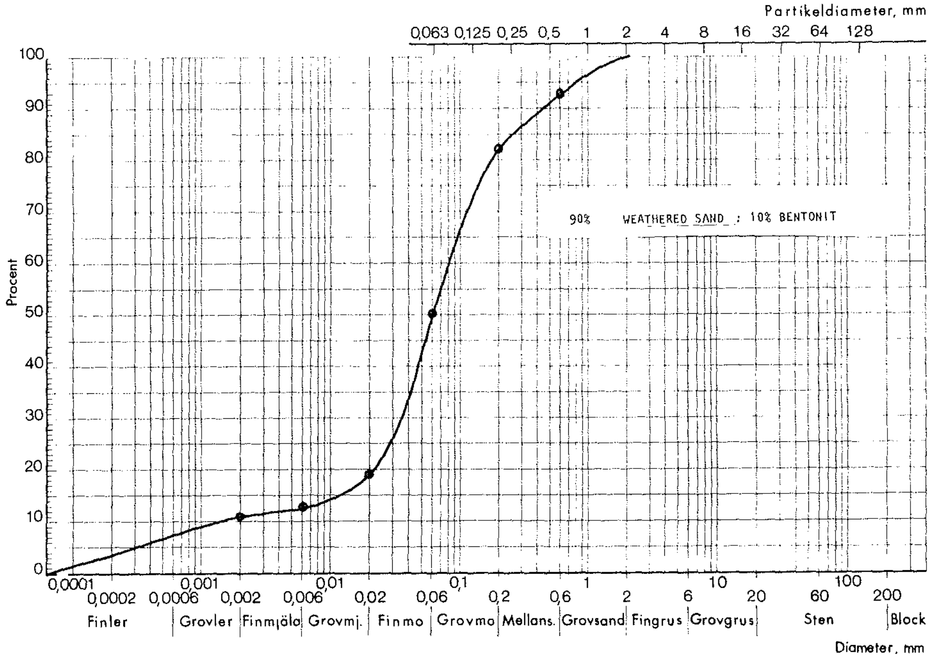


Fig. 5. Weathered coarse sand + bentonite

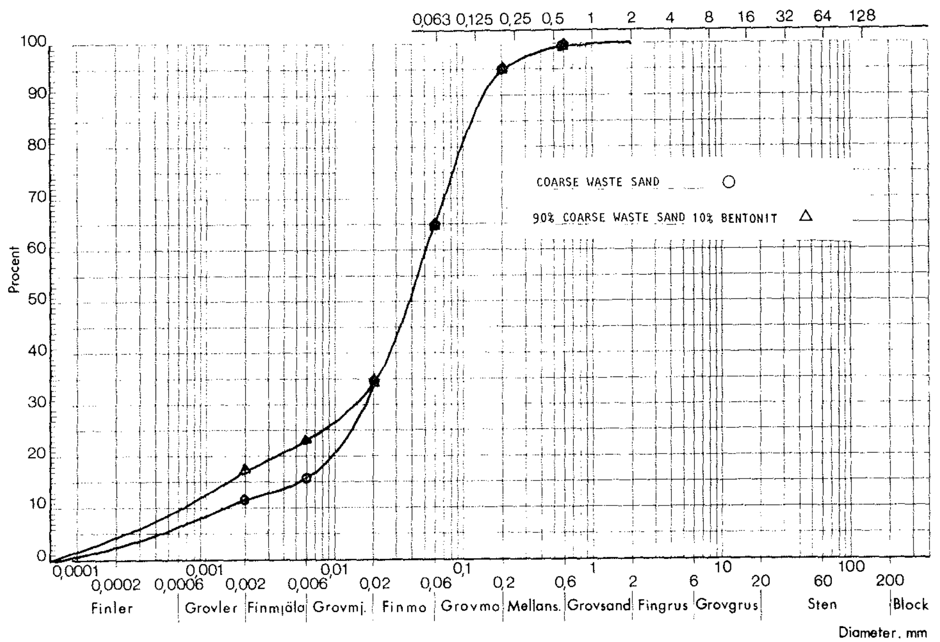


Fig. 6,7. Coarse waste sand (+ bentonite)

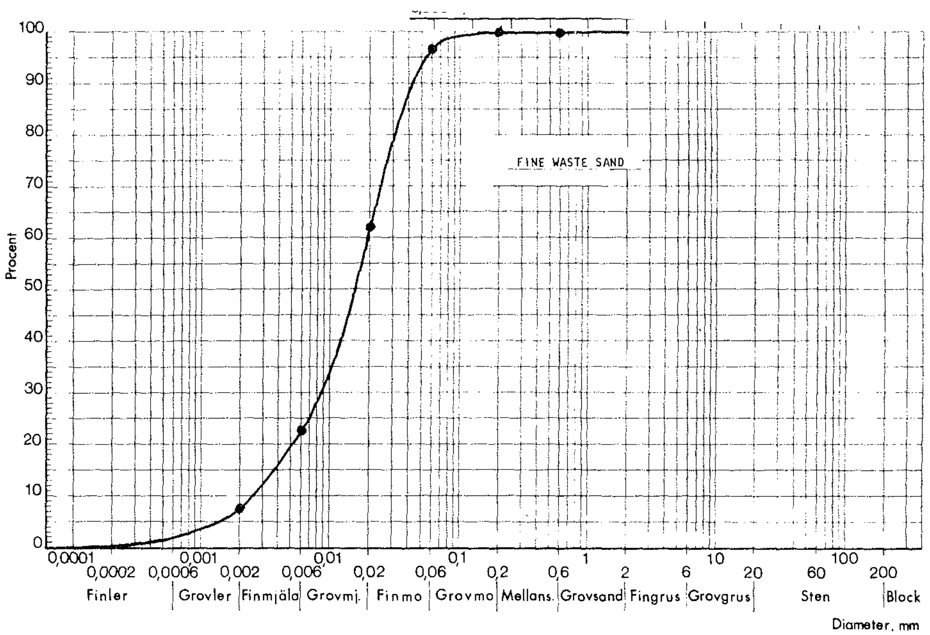


Fig. 8. Fine waste sand

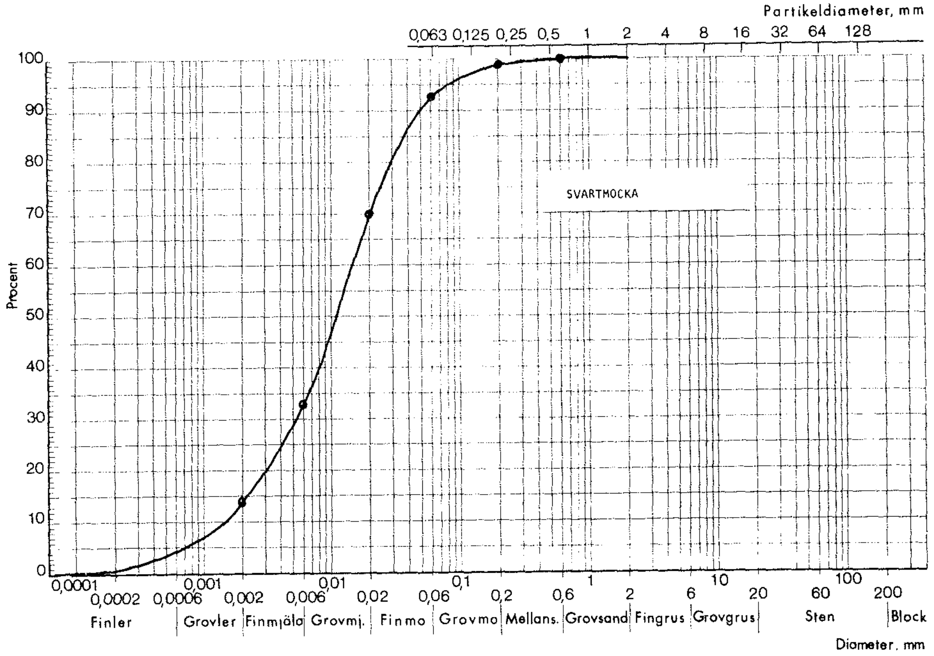


Fig. 9. Svartmocka

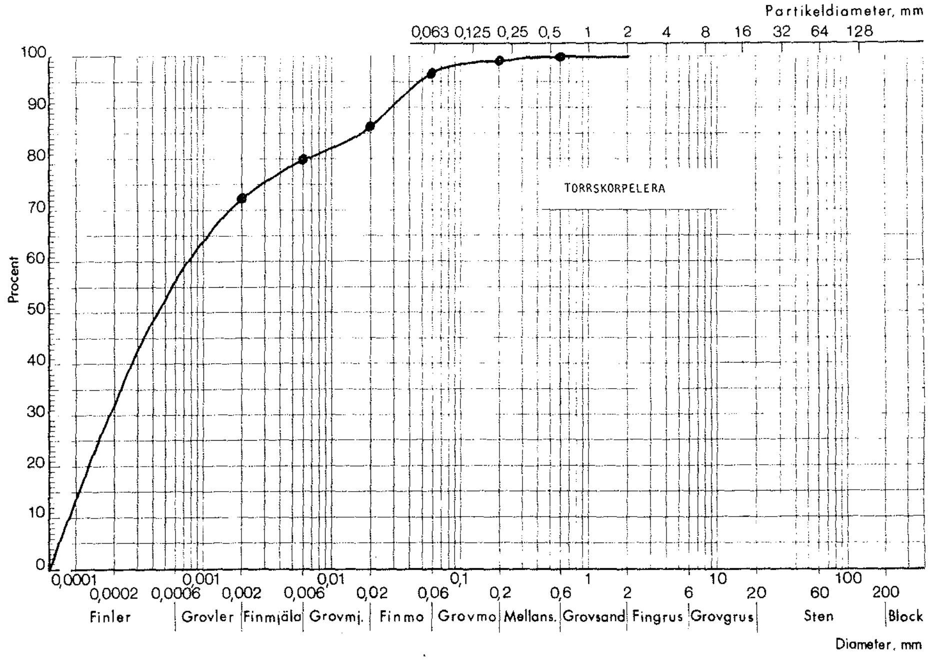


Fig. 10. Torrskorpelera

APPENDIX 2

TABLES OF RESULTS

Table 1. 95% sand + 5% bentonite

Repl. No.	Suction mwc	Water cont. vol.%	Air cont. vol.%	Diff. Coeff. D, cm2/s	Diffusivity D/Do	Air Perm. K_a, cm/min
1	0.15	30.5	2.5	3.89×10^{-5}	1.94×10^{-4}	0.00
	0.30	29.9	3.0	1.84 ''	0.90 ''	0.00
	0.50	28.5	4.4	2.31 ''	1.14 ''	0.00
	1.00	27.7	5.2	4.89 ''	2.44 ''	0.00
	6.00	22.9	10.0	1.14×10^{-4}	5.67 ''	0.08
2	0.15	31.5	1.8	2.48×10^{-5}	1.24×10^{-4}	0.00
	0.30	30.3	3.1	2.27 ''	1.14 ''	0.00
	0.50	28.9	4.5	1.20 ''	0.60 ''	0.00
	1.00	28.0	5.4	5.75 ''	2.89 ''	0.00
	6.00	23.8	9.6	3.09×10^{-4}	1.54×10^{-3}	0.82
3	0.15	31.7	1.4	4.40×10^{-5}	2.19×10^{-4}	0.00
	0.30	30.9	2.3	1.78 ''	0.90 ''	0.00
	0.50	29.5	3.6	2.37 ''	1.19 ''	0.00
	1.00	28.7	4.5	1.17×10^{-4}	5.82 ''	0.00
	6.00	24.2	8.9	3.00 ''	1.49×10^{-3}	0.93
4	0.15	31.6	1.7	1.81×10^{-5}	0.90×10^{-4}	0.00
	0.30	31.0	2.3	2.16 ''	1.10 ''	0.00
	0.50	29.5	3.8	4.70 ''	2.34 ''	0.00
	1.00	28.3	5.1	1.18×10^{-4}	5.87 ''	0.00
	6.00	22.9	10.5	-	-	1.49
5	0.15	30.4	4.1	1.57×10^{-5}	0.80×10^{-4}	0.00
	0.30	29.4	5.1	1.36 ''	0.70 ''	0.00
	0.50	28.6	6.0	4.58 ''	2.29 ''	0.00
	1.00	27.8	6.8	4.60 ''	2.29 ''	0.00
	6.00	22.2	12.3	0.97×10^{-4}	4.83 ''	0.08
6	0.15	29.2	3.9	4.28×10^{-5}	2.14×10^{-4}	0.00
	0.30	28.9	4.2	0.89 ''	0.45 ''	0.00
	0.50	28.3	4.9	5.10 ''	2.54 ''	0.00
	1.00	27.2	5.9	1.16×10^{-4}	5.77 ''	0.00
	6.00	22.8	10.3	0.99 ''	4.93 ''	0.06
Mean (coefficient of variation)						
	0.15	30.8	2.6 (42)	3.07×10^{-5}	1.53×10^{-4} (38)	0.00 (0)
	0.30	30.1	3.3 (31)	1.72 ''	0.86 '' (28)	0.00 (0)
	0.50	28.9	4.5 (17)	3.38 ''	1.68 '' (44)	0.00 (0)
	1.00	27.9	5.5 (13)	8.38 ''	4.18 '' (39)	0.00 (0)
	6.00	23.1	10.3 (10)	2.57×10^{-4}	9.15 '' (54)	0.58 (95)

Table 2. 90% sand + 10% bentonite

Repl. No.	Suction mwc	Water cont. vol.%	Air cont. vol.%	Diff. Coeff. D, cm^2/s	Diffusivity D/D_o	Air Perm. K_a, cm/min
1	0.15	34.4	1.3	3.39×10^{-5}	1.69×10^{-4}	0.00
	0.30	33.2	2.6	0.46 ''	0.25 ''	0.00
	0.50	32.9	2.8	6.00 ''	2.98 ''	0.00
	1.00	32.6	3.2	1.36 ''	0.69 ''	0.00
	6.00	30.3	5.4	1.95×10^{-4}	9.70 ''	0.30
2	0.15	34.9	1.4	6.37×10^{-5}	3.18×10^{-4}	0.00
	0.30	33.6	2.7	0.99 ''	0.49 ''	0.00
	0.50	33.0	3.3	2.20 ''	1.10 ''	0.00
	1.00	32.5	3.8	1.70 ''	0.85 ''	0.00
	6.00	29.8	6.5	2.27 ''	1.13×10^{-3}	0.02
3	0.15	35.7	0.7	4.18×10^{-5}	2.09×10^{-4}	0.00
	0.30	33.6	2.7	1.52 ''	0.75 ''	0.00
	0.50	33.2	3.2	3.41 ''	1.69 ''	0.00
	1.00	32.7	3.6	4.94 ''	2.44 ''	0.00
	6.00	31.2	5.1	1.74×10^{-4}	8.66 ''	0.03
4	0.15	34.4	2.1	4.01×10^{-5}	1.99×10^{-4}	0.00
	0.30	33.1	3.3	0.93 ''	0.45 ''	0.00
	0.50	33.0	3.5	4.09 ''	2.04 ''	0.00
	1.00	32.2	4.2	8.25 ''	4.13 ''	0.00
	6.00	29.4	7.0	2.71×10^{-4}	1.35×10^{-3}	0.01
5	0.15	36.4	1.2	0.73×10^{-5}	0.35×10^{-4}	0.00
	0.30	34.6	2.9	0.89 ''	0.45 ''	0.00
	0.50	34.1	3.5	4.5 ''	2.24 ''	0.00
	1.00	33.5	4.1	2.5 ''	1.29 ''	0.00
	6.00	29.8	7.8	2.33×10^{-4}	1.16×10^{-3}	0.04
6	0.15	34.8	0.7	5.14×10^{-5}	2.54×10^{-4}	0.00
	0.30	33.3	2.1	-	-	0.00
	0.50	33.2	2.3	2.80 ''	1.39 ''	0.00
	1.00	32.8	2.7	1.12×10^{-4}	5.57 ''	0.00
	6.00	30.4	5.0	2.48 ''	1.23×10^{-3}	0.06
Mean (coefficient of variation)						
	0.15	35.1	1.2 (39)	3.97×10^{-5}	1.97×10^{-4} (44)	0.00 (0)
	0.30	33.6	2.7 (13)	0.96 ''	0.48 '' (33)	0.00 (0)
	0.50	33.2	3.1 (14)	3.83 ''	1.82 '' (37)	0.00 (0)
	1.00	32.7	3.6 (15)	5.01 ''	2.49 '' (72)	0.00 (0)
	6.00	30.2	6.1 (17)	2.25×10^{-4}	1.12×10^{-3} (14)	0.06 (26)

Table 3. Stekenjokk moraine

Repl. No.	Suction mwc	Water cont. vol.%	Air cont. vol.%	Diff. Coeff. D, cm^2/s	Diffusivity D/Do	Air Perm. K_a, cm/min
1	0.15	24.1	3.4	2.99×10^{-5}	1.49×10^{-4}	0.00
	0.30	23.6	3.9	-	-	0.00
	0.50	23.6	3.9	1.26 ''	0.65 ''	0.05
	1.00	21.6	5.9	4.74 ''	2.34 ''	1.10
	6.00	11.9	15.6	7.54×10^{-3}	3.75×10^{-2}	6.01
2	0.15	24.5	1.9	1.76×10^{-5}	0.89×10^{-4}	0.00
	0.30	23.3	3.0	-	-	0.00
	0.50	23.3	3.0	1.89 ''	0.95 ''	0.05
	1.00	21.4	5.0	1.08×10^{-4}	5.37 ''	-
	6.00	12.4	13.9	6.43×10^{-3}	3.20×10^{-2}	4.57
3	0.15	24.5	1.8	0.67×10^{-5}	0.35×10^{-4}	0.00
	0.30	22.7	3.6	4.35 ''	2.19 ''	0.00
	0.50	22.5	3.8	3.03 ''	1.49 ''	0.03
	1.00	21.8	4.5	4.57 ''	2.29 ''	0.02
	6.00	11.6	14.7	6.74×10^{-3}	3.35×10^{-2}	3.83
4	0.15	24.5	3.0	1.59×10^{-5}	0.79×10^{-4}	0.00
	0.30	22.8	4.7	1.97 ''	0.99 ''	0.00
	0.50	22.7	4.8	1.49 ''	0.75 ''	0.02
	1.00	21.6	5.9	4.58 ''	2.29 ''	0.16
	6.00	11.9	15.6	6.60×10^{-3}	3.28×10^{-2}	3.15
5	0.15	24.4	2.0	2.78×10^{-5}	1.39×10^{-4}	0.00
	0.30	23.6	2.8	3.64 ''	1.79 ''	0.00
	0.50	23.5	2.9	2.41 ''	1.19 ''	0.02
	1.00	21.6	4.8	-	-	0.02
	6.00	11.4	15.0	7.80×10^{-3}	3.88×10^{-2}	3.31
6	0.15	24.0	1.9	-	-	0.00
	0.30	22.8	3.1	1.16×10^{-5}	0.59×10^{-4}	0.00
	0.50	21.7	4.2	3.72 ''	1.84 ''	0.61
	1.00	21.2	4.7	-	-	0.01
	6.00	12.4	13.5	4.29×10^{-3}	2.13×10^{-2}	2.12
Mean (coefficient of variation)						
	0.15	24.3	2.3 (27)	1.96×10^{-5}	0.98×10^{-4} (43)	0.00 (0)
	0.30	23.1	3.5 (18)	2.78 ''	1.39 '' (45)	0.00 (0)
	0.50	22.9	3.8 (18)	2.30 ''	1.14 '' (37)	0.13 (165)
	1.00	21.5	5.1 (11)	6.17 ''	3.07 '' (43)	1.30 (148)
	6.00	11.9	14.7 (5)	6.57×10^{-3}	3.27×10^{-2} (17)	3.80 (32)

Table 4. Bergslagen moraine

Repl. No.	Suction mwc	Water cont. vol.%	Air cont. vol.%	Diff. Coeff. D, cm^2/s	Diffusivity D/D_o	Air Perm. Ka, cm/min
1	0.15	25.2	0.9	4.02×10^{-5}	1.99×10^{-4}	0.00
	0.30	23.7	2.5	1.60 ''	0.79 ''	0.37
	0.50	23.5	2.6	5.53 ''	2.74 ''	0.03
	1.00	22.8	3.4	1.62×10^{-4}	8.06 ''	0.40
	6.00	9.3	16.9	5.48×10^{-3}	2.73×10^{-2}	1.46
2	0.15	25.8	0.5	5.90×10^{-5}	2.94×10^{-4}	0.00
	0.30	24.5	1.8	0.99 ''	0.50 ''	0.00
	0.50	24.3	2.0	7.15 ''	3.58 ''	0.13
	1.00	22.9	3.4	1.52×10^{-4}	7.56 ''	0.99
	6.00	9.0	17.3	6.07×10^{-3}	3.02×10^{-2}	1.36
3	0.15	26.1	1.9	1.87×10^{-5}	0.93×10^{-4}	0.00
	0.30	24.7	3.3	7.67 ''	3.83 ''	0.00
	0.50	24.1	3.9	2.44 ''	1.19 ''	0.04
	1.00	22.4	5.6	2.61×10^{-4}	1.29×10^{-3}	3.09
	6.00	8.8	19.2	5.78×10^{-3}	2.87×10^{-2}	1.14
4	0.15	25.9	1.9	1.99×10^{-5}	0.99×10^{-4}	0.00
	0.30	25.7	2.1	4.42 ''	2.19 ''	0.37
	0.50	24.0	3.8	-	-	0.08
	1.00	24.5	5.4	5.59×10^{-4}	2.78×10^{-3}	-
	6.00	8.9	18.9	6.22×10^{-3}	3.09×10^{-2}	1.05
5	0.15	25.7	1.2	2.99×10^{-5}	1.49×10^{-4}	0.00
	0.30	24.1	2.8	2.81 ''	1.39 ''	0.00
	0.50	23.9	3.0	3.28 ''	1.64 ''	0.07
	1.00	22.7	4.2	3.84 ''	1.91×10^{-3}	1.38
	6.00	9.9	17.0	6.56×10^{-3}	3.26×10^{-2}	2.08
6	0.15	25.8	0.3	1.48×10^{-5}	0.75×10^{-4}	0.00
	0.30	24.1	2.1	3.06 ''	1.54 ''	0.00
	0.50	23.4	2.7	3.29 ''	1.64 ''	0.18
	1.00	22.1	4.1	5.28×10^{-4}	2.63×10^{-3}	4.82
	6.00	10.3	15.9	4.98×10^{-3}	2.48×10^{-2}	1.00
Mean (coefficient of variation)						
	0.15	25.8	1.1 (54)	3.04×10^{-5}	1.52×10^{-4} (50)	0.00 (0)
	0.30	24.3	2.6 (22)	3.43 ''	1.71 '' (64)	0.12 (145)
	0.50	23.9	3.0 (22)	4.34 ''	2.16 '' (41)	0.09 (58)
	1.00	22.5	4.3 (20)	3.41×10^{-4}	1.69×10^{-3} (48)	2.14 (75)
	6.00	9.4	17.5 (6)	5.85×10^{-3}	2.91×10^{-2} (8)	1.35 (27)

Table 5. Weathered waste sand + bentonite

Repl. No.	Suction mwc	Water cont. vol.%	Air cont. vol.%	Diff. Coeff. D, cm^2/s	Diffusivity D/D_o	Air Perm. K_a, cm/min
1	0.15	43.0	1.8	2.73×10^{-5}	1.34×10^{-4}	0.00
	0.30	42.7	2.2	0.96 ''	0.49 ''	0.01
	0.50	42.6	2.3	3.65 ''	1.84 ''	0.01
	1.00	42.4	2.5	4.93 ''	2.44 ''	0.01
	6.00	34.5	10.3	4.39 ''	2.19 ''	0.04
2	0.15	40.9	3.4	6.87×10^{-5}	3.43×10^{-4}	0.00
	0.30	40.8	3.5	2.36 ''	1.19 ''	0.02
	0.50	40.7	3.6	2.88 ''	1.44 ''	0.01
	1.00	40.7	3.6	4.43 ''	2.19 ''	0.02
	6.00	34.3	10.0	3.13 ''	1.54 ''	0.02
3	0.15	43.3	0.9	1.45×10^{-5}	0.75×10^{-4}	0.00
	0.30	42.7	1.5	-	-	0.01
	0.50	42.6	1.6	1.32 ''	0.65 ''	0.01
	1.00	42.3	1.8	2.18 ''	1.10 ''	0.02
	6.00	34.1	10.0	1.45×10^{-4}	7.26 ''	0.04
4	0.15	43.4	1.1	4.80×10^{-5}	2.39×10^{-4}	0.00
	0.30	42.8	1.8	7.04 ''	3.48 ''	0.02
	0.50	42.6	2.0	0.73 ''	0.35 ''	0.01
	1.00	42.3	2.2	0.29 ''	0.10 ''	0.02
	6.00	34.2	10.4	8.91 ''	4.43 ''	0.04
5	0.15	43.5	0.8	7.38×10^{-5}	3.68×10^{-4}	0.00
	0.30	43.0	1.3	3.84 ''	1.89 ''	0.03
	0.50	42.8	1.5	1.17 ''	0.59 ''	0.01
	1.00	42.5	1.8	0.73 ''	0.35 ''	0.02
	6.00	33.8	10.5	9.76 ''	4.88 ''	0.04
6	0.15	43.4	0.8	2.02×10^{-5}	0.99×10^{-4}	0.00
	0.30	42.4	1.7	(1.15×10^{-4})	(5.72 '')	0.01
	0.50	42.4	1.7	1.17×10^{-5}	0.60 ''	0.01
	1.00	42.4	1.7	2.41 ''	1.19 ''	0.04
	6.00	34.5	9.6	1.22×10^{-4}	6.07 ''	0.04
Mean (coefficient of variation)						
	0.15	42.9	1.5 (64)	4.21×10^{-5}	2.09×10^{-4} (55)	0.00 (0)
	0.30	42.4	2.0 (38)	5.15 ''	2.56 '' (73)	0.02 (46)
	0.50	42.3	2.1 (33)	1.82 ''	0.91 '' (59)	0.01 (0)
	1.00	42.1	2.3 (26)	2.49 ''	1.23 '' (70)	0.02 (45)
	6.00	34.3	10.1 (3)	8.48 ''	4.40 '' (46)	0.04 (19)

Table 6. Coarse waste sand

Repl. No.	Suction mwc	Water cont. vol.%	Air cont. vol.%	Diff. Coeff. D, cm^2/s	Diffusivity D/D$_o$	Air Perm. K$_a$, cm/min
1	0.15	36.4	0.7	1.70 x 10^{-5}	0.85 x 10^{-4}	0.00
	0.30	35.9	1.1	1.48 ''	0.75 ''	0.04
	0.50	35.9	1.1	3.40 ''	1.69 ''	0.00
	1.00	34.7	2.4	4.99 ''	2.49 ''	-
	6.00	27.2	9.9	8.79 x 10^{-4}	4.37 x 10^{-3}	0.35
2	0.15	31.5	4.9	1.27 x 10^{-5}	0.65 x 10^{-4}	0.00
	0.30	31.4	5.0	0.90 ''	0.45 ''	0.06
	0.50	31.3	5.1	3.66 ''	1.84 ''	0.09
	1.00	30.7	5.7	1.79 x 10^{-4}	8.91 ''	-
	6.00	26.5	9.9	5.95 ''	2.96 x 10^{-3}	0.17
3	0.15	33.3	3.8	0.93 x 10^{-5}	0.45 x 10^{-4}	0.00
	0.30	33.1	3.9	1.18 ''	0.59 ''	0.06
	0.50	32.8	4.2	2.00 ''	0.99 ''	0.07
	1.00	32.2	4.9	9.05 ''	4.53 ''	-
	6.00	28.1	8.9	6.09 x 10^{-4}	3.03 x 10^{-3}	0.47
4	0.15	34.9	0.9	1.24 x 10^{-5}	0.59 x 10^{-4}	0.00
	0.30	34.4	1.5	0.70 ''	0.35 ''	0.02
	0.50	34.1	1.7	4.95 ''	2.49 ''	0.03
	1.00	33.4	2.4	-	-	-
	6.00	28.3	7.5	-	-	-
5	0.15	33.7	0.6	0.52 x 10^{-5}	0.25 x 10^{-4}	0.00
	0.30	33.5	0.8	0.67 ''	0.35 ''	0.05
	0.50	33.4	0.9	4.48 ''	2.24 ''	0.18
	1.00	33.1	1.2	7.20 ''	3.58 ''	-
	6.00	28.9	5.4	7.40 x 10^{-4}	3.68 x 10^{-3}	0.26
6	0.15	34.1	0.9	0.82 x 10^{-5}	0.40 x 10^{-4}	0.00
	0.30	33.8	1.2	0.65 ''	0.35 ''	0.02
	0.50	33.8	1.2	4.44 ''	2.19 ''	0.08
	1.00	33.1	1.7	1.72 ''	0.86 ''	-
	6.00	28.4	6.6	7.18 x 10^{-4}	3.57 x 10^{-3}	0.26
Mean (coefficient of variation)						
	0.15	34.0	2.0 (86)	1.08 x 10^{-5}	0.53 x 10^{-4} (36)	0.00 (0)
	0.30	33.7	2.2 (71)	0.93 ''	0.47 '' (32)	0.04 (42)
	0.50	33.6	2.3 (68)	3.84 ''	1.91 '' (26)	0.08 (75)
	1.00	32.9	3.0 (54)	8.18 ''	4.07 '' (46)	-
	6.00	27.9	8.0 (21)	7.08 x 10^{-4}	3.52 x 10^{-3} (15)	0.31 (32)

Table 7. Coarse (unweathered) waste sand + bentonite

Repl. No.	Suction mwc	Water cont. vol.%	Air cont. vol.%	Diff. Coeff. D, cm^2/s	Diffusivity D/D$_o$	Air Perm. K$_a$, cm/min
1	0.15	44.6	1.1	-	-	0.00
	0.30	43.8	1.9	9.03×10^{-5}	4.48×10^{-4}	-
	0.50	42.7	3.0	7.25 ''	3.63 ''	(20.0)
	1.00	41.3	4.4	1.81×10^{-4}	9.01 ''	8.7
	6.00	38.3	7.4	2.63×10^{-3}	1.31×10^{-2}	-
2	0.15	41.8	2.9	1.33×10^{-5}	0.65×10^{-4}	0.00
	0.30	40.4	4.3	2.46 ''	1.24 ''	1.54
	0.50	39.2	5.5	1.33 ''	0.65 ''	0.02
	1.00	37.6	7.1	1.32×10^{-4}	6.57 ''	7.74
	6.00	34.3	10.4	4.03×10^{-3}	2.00×10^{-2}	-
3	0.15	44.0	0.6	0.67×10^{-5}	0.35×10^{-4}	0.00
	0.30	42.7	1.9	4.67 ''	2.34 ''	1.83
	0.50	41.8	2.8	6.77 ''	3.38 ''	-
	1.00	40.2	4.4	-	-	1.11
	6.00	37.6	7.0	0.97×10^{-3}	0.47×10^{-2}	-
4	0.15	46.1	0.6	0.91×10^{-5}	0.45×10^{-4}	0.00
	0.30	45.5	1.2	5.96 ''	2.98 ''	1.77
	0.50	44.3	2.4	6.56 ''	3.28 ''	0.01
	1.00	42.6	4.1	5.90 ''	2.94 ''	(0)
	6.00	39.5	7.2	3.07×10^{-3}	1.53×10^{-2}	-
5	0.15	43.8	0.9	2.28×10^{-5}	1.14×10^{-4}	0.00
	0.30	43.0	1.7	4.45 ''	2.24 ''	0.00
	0.50	41.7	3.0	5.62 ''	2.79 ''	13.80
	1.00	39.9	4.8	5.60 ''	2.79 ''	-
	6.00	37.0	7.7	3.34×10^{-3}	1.66×10^{-2}	-
6	0.15	42.2	3.1	1.29×10^{-5}	0.65×10^{-4}	0.00
	0.30	41.9	3.4	8.05 ''	4.03 ''	0.68
	0.50	40.6	4.7	-	-	-
	1.00	39.2	6.1	-	-	-
	6.00	36.1	9.2	3.90×10^{-3}	1.94×10^{-2}	-
Mean (coefficient of variation)						
	0.15	43.7	1.6 (69)	1.30×10^{-5}	0.65×10^{-4} (42)	0.00 (0)
	0.30	42.9	2.4 (45)	5.77 ''	2.89 '' (38)	1.20 (60)
	0.50	41.7	3.6 (32)	5.50 ''	2.78 '' (39)	8.50 (100)
	1.00	40.1	5.2 (21)	1.07×10^{-4}	5.33 '' (49)	4.4 (88)
	6.00	37.1	8.2 (15)	2.99×10^{-3}	1.49×10^{-2} (34)	-

Table 8. Fine waste sand

Repl. No.	Suction mwc	Water cont. vol.%	Air cont. vol.%	Diff. Coeff. D, cm^2/s	Diffusivity D/D_o	Air Perm. Ka, cm/min
1	0.15	45.7	1.1	4.72×10^{-6}	0.25×10^{-4}	0.00
	0.30	44.3	2.5	3.43 ''	0.15 ''	0.00
	0.50	41.3	5.5	2.65 ''	0.14 ''	(0.40)
	1.00	39.4	7.4	1.11×10^{-4}	5.52 ''	0.01
	6.00	37.2	9.6	1.39 ''	6.92 ''	0.15
2	0.15	45.8	1.7	6.54×10^{-6}	0.35×10^{-4}	0.00
	0.30	43.5	4.0	8.31 ''	0.39 ''	0.00
	0.50	40.1	7.4	5.84 ''	0.30 ''	0.09
	1.00	39.3	8.2	2.00×10^{-5}	0.99 ''	0.01
	6.00	36.7	10.8	9.00 ''	4.48 ''	0.31
3	0.15	46.0	2.0	7.95×10^{-6}	0.39×10^{-4}	0.00
	0.30	43.8	4.2	1.03×10^{-5}	0.50 ''	0.00
	0.50	40.6	7.4	1.74 ''	0.85 ''	0.00
	1.00	39.5	8.5	2.07×10^{-4}	1.03×10^{-3}	0.01
	6.00	37.1	10.9	1.33 ''	0.66 ''	0.39
4	0.15	46.7	1.0	8.73×10^{-6}	0.45×10^{-4}	0.00
	0.30	43.9	3.8	5.77 ''	0.30 ''	0.00
	0.50	40.7	7.0	6.96 ''	0.35 ''	0.00
	1.00	39.7	8.0	-	-	0.01
	6.00	37.1	10.6	1.05×10^{-4}	5.22 ''	0.25
5	0.15	47.2	0.3	1.10×10^{-5}	0.55×10^{-4}	0.00
	0.30	45.4	2.1	4.73×10^{-6}	0.25 ''	0.00
	0.50	42.5	4.9	1.93 ''	0.10 ''	0.00
	1.00	41.9	5.5	9.50×10^{-5}	4.73 ''	0.01
	6.00	39.4	8.1	1.24×10^{-4}	6.17 ''	0.14
6	0.15	47.5	0.6	7.82×10^{-6}	0.39×10^{-4}	0.00
	0.30	46.7	1.4	2.11 ''	0.10 ''	0.00
	0.50	41.5	6.6	8.69 ''	0.45 ''	0.00
	1.00	40.5	7.6	1.64×10^{-5}	0.79 ''	0.01
	6.00	38.2	9.9	8.30 ''	4.13 ''	2.48
Mean (coefficient of variation)						
	0.15	46.5	1.1 (53)	7.79×10^{-6}	0.40×10^{-4} (22)	0.00 (0)
	0.30	44.6	3.0 (35)	5.78 ''	0.28 '' (50)	0.00 (0)
	0.50	41.1	6.5 (15)	7.25 ''	0.37 '' (68)	0.08 (182)
	1.00	40.1	7.5 (13)	8.99×10^{-5}	4.47 '' (78)	0.01 (0)
	6.00	37.6	10.0 (10)	1.12×10^{-4}	5.59 '' (19)	0.62 (135)

Table 9. Svartmocka silt

Repl. No.	Suction mwc	Water cont. vol.%	Air cont. vol.%	Diff. Coeff. D, cm2/s	Diffusivity D/D_o	Air Perm. K_a, cm/min
1	0.15	69.1	1.9	2.11 x 10^{-6}	0.10 x 10^{-4}	0.00
	0.30	67.1	3.9	4.35 ''	0.20 ''	0.00
	0.50	66.1	4.9	1.15 x 10^{-5}	0.59 ''	0.00
	1.00	62.5	8.5	-	-	-
	6.00	55.8	15.2	1.74 x 10^{-3}	8.63 x 10^{-3}	-
2	0.15	69.9	0.7	2.00 x 10^{-6}	0.10 x 10^{-4}	0.00
	0.30	68.3	2.3	1.81 ''	0.10 ''	0.00
	0.50	66.1	4.5	4.04 x 10^{-5}	1.99 ''	0.00
	1.00	62.9	7.7	-	-	0.02
	6.00	58.0	12.6	4.26 x 10^{-4}	2.12 x 10^{-3}	0.07
3	0.15	(71.1)	(0.0)	4.41 x 10^{-6}	0.20 x 10^{-4}	0.00
	0.30	67.9	2.8	3.24 ''	0.15 ''	0.00
	0.50	65.6	5.2	3.15 x 10^{-5}	1.59 ''	0.00
	1.00	63.8	7.0	-	-	0.16
	6.00	56.3	14.5	1.41 x 10^{-4}	0.70 x 10^{-3}	0.33
4	0.15	70.2	1.1	3.81 x 10^{-6}	0.20 x 10^{-4}	0.00
	0.30	67.8	3.5	2.63 ''	0.15 ''	0.00
	0.50	65.5	5.8	3.25 x 10^{-5}	1.64 ''	0.00
	1.00	61.4	9.9	9.37 x 10^{-4}	4.66 x 10^{-3}	0.22
	6.00	55.7	15.6	1.26 x 10^{-3}	6.27 ''	-
5	0.15	71.5	0.9	4.71 x 10^{-6}	0.25 x 10^{-4}	0.00
	0.30	69.0	3.5	-	-	0.00
	0.50	65.7	6.8	2.55 x 10^{-5}	1.29 ''	0.00
	1.00	60.5	12.0	9.61 x 10^{-4}	4.78 x 10^{-3}	0.43
	6.00	54.8	17.6	9.60 ''	4.78 ''	0.59
6	0.15	69.0	1.6	3.71 x 10^{-6}	0.20 x 10^{-4}	0.00
	0.30	66.7	3.9	2.33 ''	0.10 ''	0.00
	0.50	64.9	5.7	1.99 x 10^{-5}	0.99 ''	0.00
	1.00	61.1	9.5	1.05 x 10^{-3}	5.20 x 10^{-3}	0.01
	6.00	56.1	14.5	0.46 ''	2.24 ''	0.38
Mean (coefficient of variation)						
	0.15	70.1	1.0 (34)	3.40 x 10^{-6}	0.17 x 10^{-4} (35)	0.00 (0)
	0.30	67.8	3.3 (18)	2.87 ''	0.14 '' (28)	0.00 (0)
	0.50	65.6	5.5 (13)	2.69 x 10^{-5}	1.35 '' (34)	0.00 (0)
	1.00	62.0	9.1 (18)	9.81 x 10^{-4}	4.88 x 10^{-3} (5)	0.17 (90)
	6.00	56.1	15.0 (10)	8.32 ''	4.12 '' (66)	0.34 (54)

Table 10. Torrskorpelera clay

Repl. No.	Suction mwc	Water cont. vol.%	Air cont. vol.%	Diff. Coeff. D, cm^2/s	Diffusivity D/D_o	Air Perm. K_a, cm/min
1	0.15	53.7	1.9	2.11×10^{-6}	0.10×10^{-4}	0.00
	0.30					
	0.50	53.6	2.0	1.43 ''	0.10 ''	0.00
	1.00	52.8	2.7	3.29 ''	0.15 ''	0.01
	6.00	49.5	6.1	2.00 ''	0.10 ''	0.01
2	0.15	53.8	0.7	3.55×10^{-6}	0.20×10^{-4}	0.00
	0.30					
	0.50	53.8	0.7	4.34 ''	0.20 ''	0.00
	1.00	52.6	2.0	3.90 ''	0.20 ''	0.01
	6.00	48.7	5.8	3.52 ''	0.20 ''	0.01
3	0.15	52.7	1.5	0.41×10^{-6}	0.05×10^{-4}	0.00
	0.30					
	0.50	52.4	1.8	7.64 ''	0.40 ''	0.00
	1.00	51.3	2.8	4.78 ''	0.25 ''	0.01
	6.00	47.9	6.3	6.04 ''	0.30 ''	0.01
4	0.15	53.8	1.7	-	-	0.00
	0.30					
	0.50	53.6	1.9	-	-	0.00
	1.00	52.7	2.8	3.44×10^{-6}	0.20×10^{-4}	0.01
	6.00	48.0	7.5	8.86 ''	0.45 ''	0.01
5	0.15	53.8	1.8	0.42×10^{-6}	0.05×10^{-4}	0.00
	0.30					
	0.50	53.7	1.9	2.57 ''	0.15 ''	0.00
	1.00	52.9	2.8	4.28 ''	0.20 ''	0.01
	6.00	49.0	6.6	3.52 ''	0.20 ''	0.01
6	0.15	52.2	2.5	4.82×10^{-6}	0.25×10^{-4}	0.00
	0.30					
	0.50	52.1	2.7	8.61 ''	0.45 ''	0.00
	1.00	51.2	3.6	5.00 ''	0.25 ''	0.01
	6.00	47.3	7.4	-	-	0.01
Mean (coefficient of variation)						
	0.15	53.3	1.7 (33)	2.26×10^{-6}	0.13×10^{-4} (61)	0.00 (0)
	0.30					
	0.50	53.2	1.8 (32)	4.92 ''	0.26 '' (54)	0.00 (0)
	1.00	52.2	2.8 (16)	4.12 ''	0.21 '' (14)	0.01 (0)
	6.00	48.4	6.6 (10)	4.79 ''	0.25 '' (48)	0.01 (0)

Table 11. Highly humified peat

Repl. No.	Suction mwc	Water cont. vol.%	Air cont. vol.%	Diff. Coeff. D, cm²/s	Diffusivity D/D$_o$	Air Perm. Ka, cm/min
1	0.15	86.1	4.1	1.36×10^{-5}	0.70×10^{-4}	0.00
	0.30	84.4	5.7	5.67 ''	2.84 ''	0.00
	0.50	81.4	8.7	7.52 ''	3.73 ''	1.70
	1.00	72.9	17.2	1.08×10^{-3}	5.37×10^{-3}	3.22
	6.00	58.0	32.1	3.95 ''	1.97×10^{-2}	27.90
2	0.15	86.4	3.3	5.15×10^{-5}	2.59×10^{-4}	0.00
	0.30	85.6	4.1	2.03 ''	0.99 ''	0.00
	0.50	83.0	6.7	1.04 ''	0.49 ''	5.40
	1.00	73.8	15.9	1.10×10^{-3}	5.47×10^{-3}	1.57
	6.00	54.6	35.1	4.88 ''	2.43×10^{-2}	29.70
3	0.15	86.7	3.3	-	-	0.00
	0.30	85.0	5.0	2.74×10^{-5}	1.34×10^{-4}	0.00
	0.50	81.4	8.6	1.39 ''	0.70 ''	2.05
	1.00	72.7	17.3	1.38×10^{-3}	6.86×10^{-3}	3.83
	6.00	56.5	33.5	4.84 ''	2.41×10^{-2}	27.60
4	0.15	85.1	5.1	1.41×10^{-5}	0.69×10^{-4}	0.00
	0.30	84.6	5.6	1.76 ''	0.90 ''	0.00
	0.50	82.6	7.6	0.30 ''	0.15 ''	0.00
	1.00	73.1	17.1	-	-	0.34
	6.00	58.8	31.3	3.34×10^{-3}	1.66×10^{-2}	24.30
5	0.15	86.8	3.0	9.10×10^{-5}	4.53×10^{-4}	0.00
	0.30	86.0	3.8	1.33 ''	0.65 ''	0.00
	0.50	84.5	5.3	0.90 ''	0.45 ''	0.13
	1.00	75.1	14.8	3.97×10^{-3}	1.98×10^{-2}	0.28
	6.00	55.9	33.9	3.62 ''	1.80 ''	14.70
6	0.15	85.5	4.6	2.40×10^{-5}	1.19×10^{-4}	0.00
	0.30	85.5	4.6	1.57 ''	0.80 ''	0.00
	0.50	84.6	5.5	8.15 ''	4.08 ''	0.04
	1.00	74.8	15.3	3.58×10^{-3}	1.78×10^{-2}	0.41
	6.00	58.5	31.6	2.85 ''	1.42 ''	2.80
Mean (coefficient of variation)						
	0.15	86.1	3.9 (19)	3.88×10^{-5}	1.94×10^{-4} (76)	0.00 (0)
	0.30	85.2	4.8 (15)	2.51 ''	1.25 '' (59)	0.00 (0)
	0.50	82.9	7.1 (23)	3.22 ''	1.60 '' (98)	1.60 (119)
	1.00	73.7	16.3 (6)	2.22×10^{-3}	1.11×10^{-2} (58)	1.60 (89)
	6.00	57.1	32.9 (4)	3.91 ''	1.95 '' (19)	21.10 (45)

Table 12. Poorly humified peat

Repl. No.	Suction mwc	Water cont. vol.%	Air cont. vol.%	Diff. Coeff. D, cm^2/s	Diffusivity D/D_o	Air Perm. K_a, cm/min
1	0.15	87.4	4.7	2.87×10^{-5}	1.44×10^{-4}	0.00
	0.30	85.5	6.6	1.23 ''	0.60 ''	0.00
	0.50	81.0	11.2	9.44 ''	4.68 ''	1.34
	1.00	72.1	20.0	1.90×10^{-3}	9.45×10^{-3}	3.76
	6.00	50.1	42.0	1.04×10^{-2}	5.18×10^{-2}	15.12
2	0.15	86.2	6.2	0.94×10^{-5}	0.45×10^{-4}	0.00
	0.30	83.8	8.6	2.96 ''	1.49 ''	0.00
	0.50	79.5	13.0	7.05 ''	3.52 ''	0.36
	1.00	70.7	21.7	1.91×10^{-3}	9.50×10^{-3}	-
	6.00	45.7	46.7	1.36×10^{-2}	6.79×10^{-2}	23.90
3	0.15	87.5	4.6	0.69×10^{-5}	0.35×10^{-4}	0.00
	0.30	86.3	5.8	1.97 ''	0.99 ''	0.00
	0.50	84.6	7.6	1.85 ''	0.95 ''	0.00
	1.00	73.8	18.3	0.48×10^{-3}	2.39×10^{-3}	0.30
	6.00	51.5	40.6	5.01 ''	2.49×10^{-2}	6.87
4	0.15	86.4	5.8	-	-	0.00
	0.30	85.4	6.9	0.27×10^{-5}	0.15×10^{-4}	0.00
	0.50	85.2	7.1	1.97 ''	0.99 ''	0.07
	1.00	73.7	18.5	0.75×10^{-3}	3.73×10^{-3}	0.13
	6.00	47.9	44.4	9.02 ''	4.49×10^{-2}	9.29
5	0.15	87.9	4.1	3.55×10^{-5}	1.74×10^{-4}	0.00
	0.30	87.5	4.6	3.27 ''	1.64 ''	0.00
	0.50	86.7	5.4	1.31 ''	0.65 ''	0.00
	1.00	75.1	16.9	0.26×10^{-3}	1.29×10^{-3}	0.15
	6.00	48.7	43.3	1.12×10^{-2}	5.56×10^{-2}	7.94
6	0.15	89.6	3.3	1.13×10^{-5}	0.55×10^{-4}	0.00
	0.30	88.8	4.1	-	-	0.00
	0.50	88.4	4.5	5.51 ''	2.74 ''	0.00
	1.00	76.6	16.3	1.15×10^{-3}	5.72×10^{-3}	-
	6.00	-	-	-	-	8.26
Mean (coefficient of variation)						
	0.15	87.5	4.8 (21)	1.84×10^{-5}	0.91×10^{-4} (63)	0.00 (0)
	0.30	86.2	6.1 (25)	1.94 ''	0.97 '' (57)	0.00 (0)
	0.50	84.2	8.1 (37)	4.52 ''	2.26 '' (67)	0.30 (161)
	1.00	73.7	18.6 (10)	1.08×10^{-3}	5.35×10^{-3} (60)	1.10 (139)
	6.00	48.8	43.4 (5)	9.85 ''	4.90×10^{-2} (29)	12.00 (51)

APPENDIX 3

REGRESSION ANALYSIS ON DIFFUSIVITY AS A FUNCTION OF AIR-FILLED POROSITY

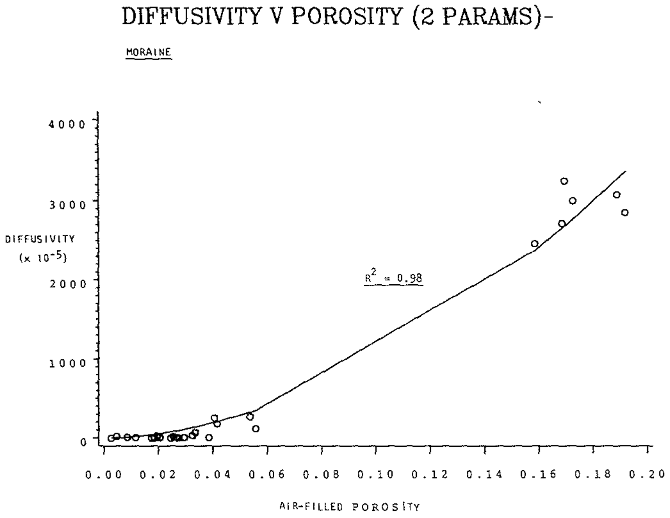


Fig. 1. MORAINE. $D/D_o = 0.7E_g^{1.8}$

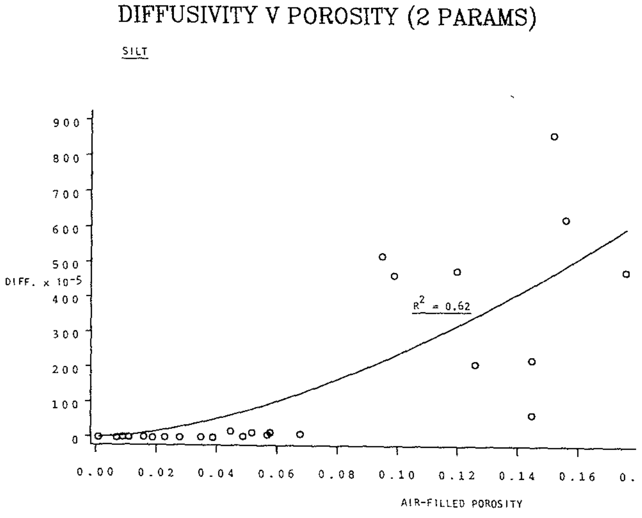


Fig. 2. SILT. $D/D_o = 0.1E_g^{1.6}$

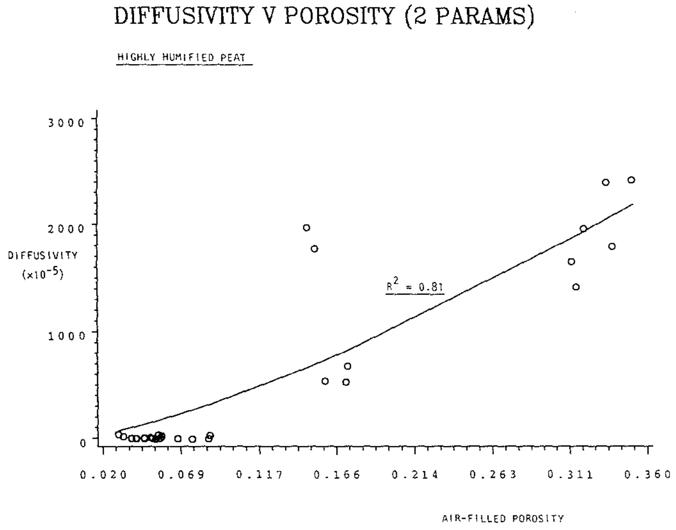


Fig. 3. High H peat. $D/D_o = 0.1E_g^{1.4}$

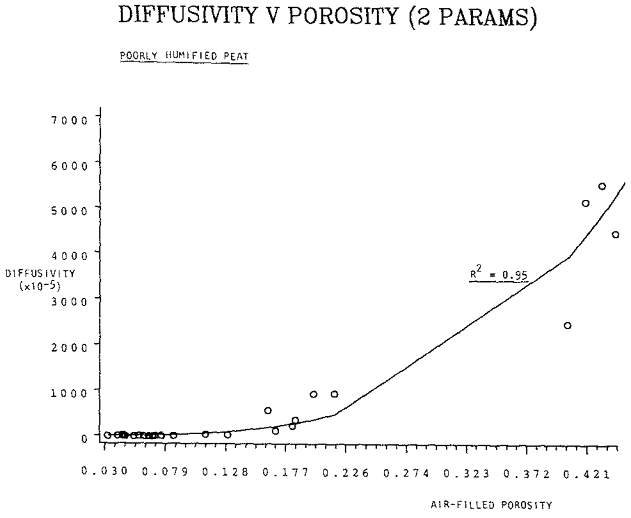


Fig. 4. Low H peat. $D/D_o = 0.8E_g^{3.}$

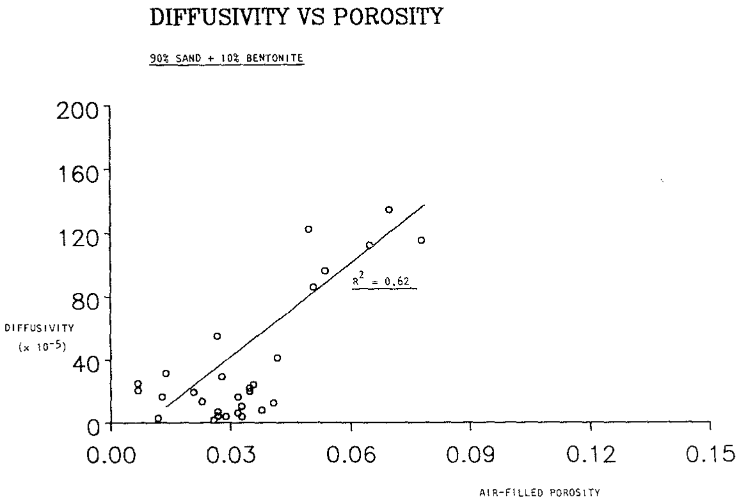


Fig. 5. Sand + bentonite. $D/D_o = 0.02(E_g - 0.01)$

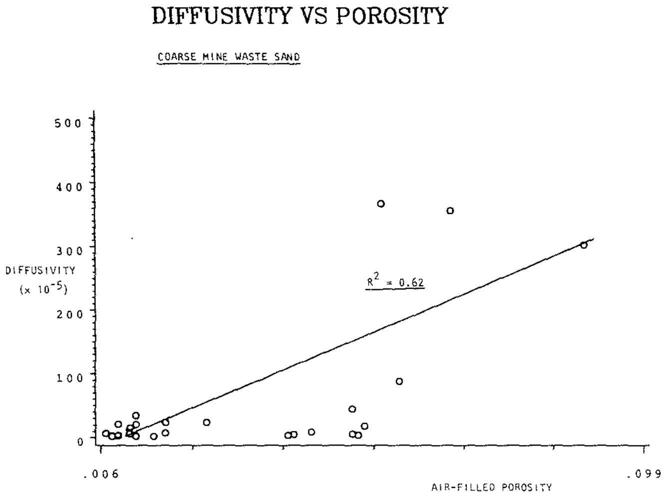


Fig. 6. Coarse waste sand.
$D/D_o = 0.04(E_g - 0.01)$

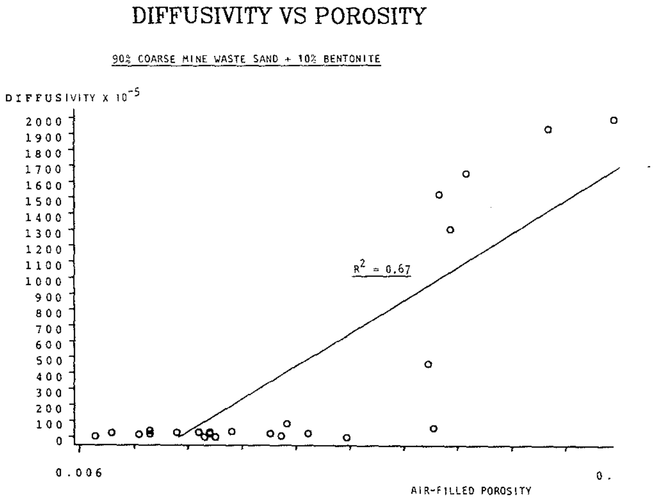


Fig. 7. Coarse waste sand + ben.
$D/D_o = 0.2(E_g - 0.02)$

APPENDIX 4

MOISTURE RETENTION CURVES

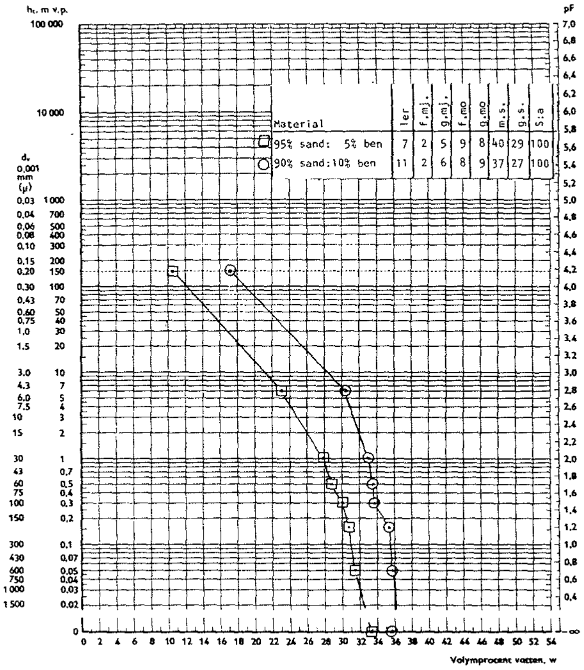


Fig. 1. Sand + bentonite

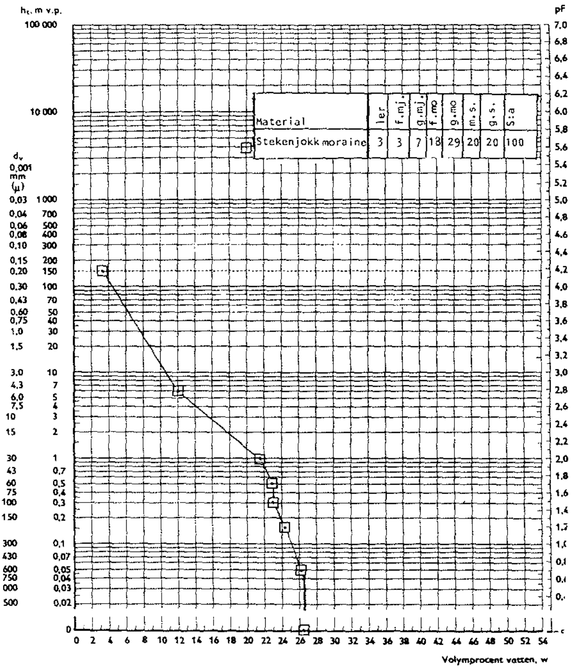


Fig. 2. Stekenjokk moraine

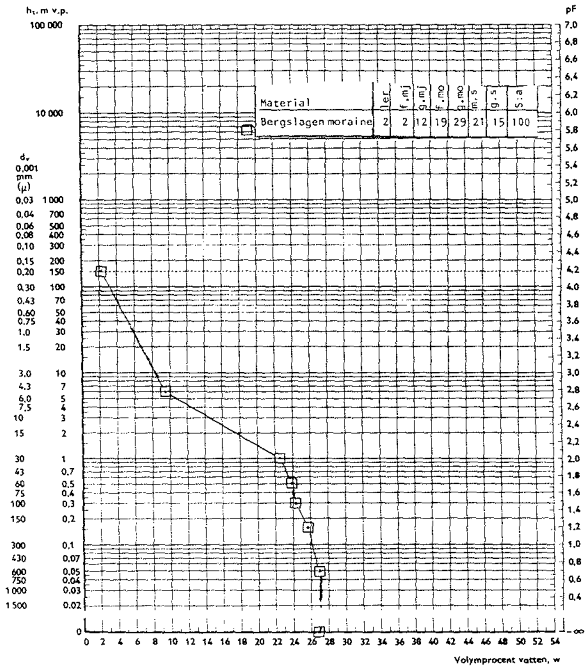


Fig. 3. Bergslagen moraine

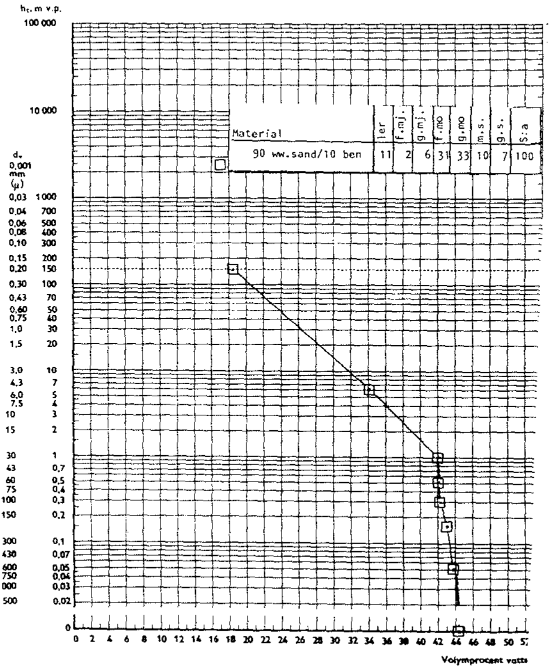


Fig. 4. Weathered waste sand + b

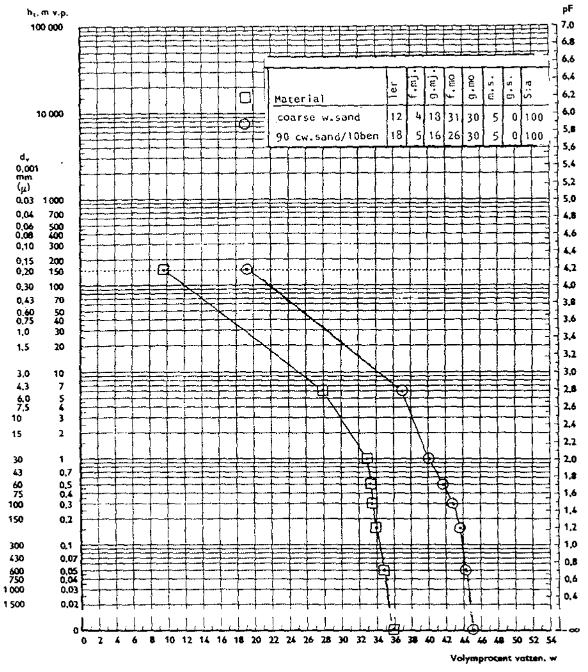


Fig. 5. Coarse waste sand (O)
Coarse waste sand + ben (□)

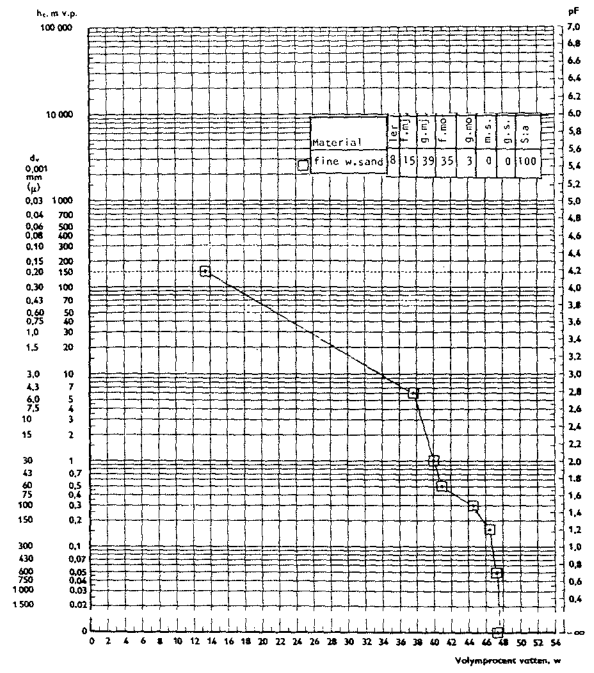


Fig. 6. Fine waste sand

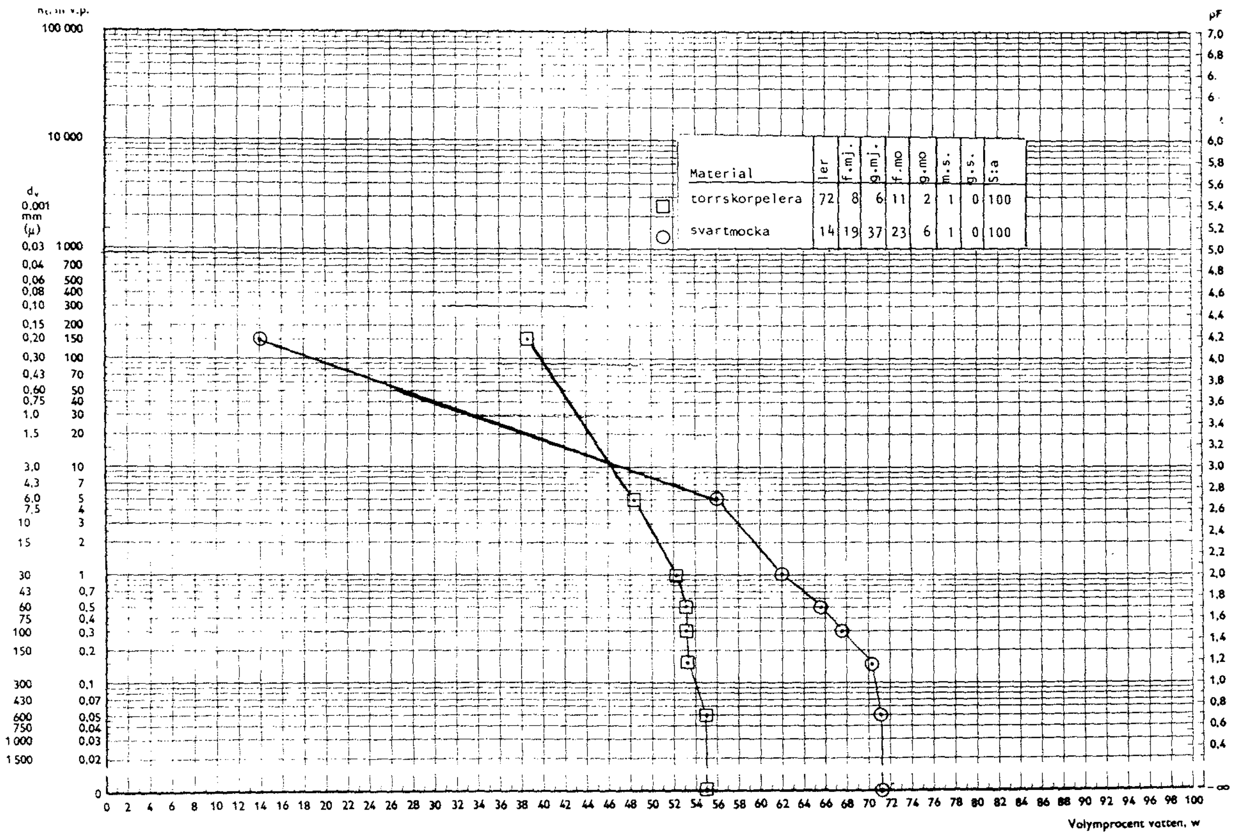


Fig. 7. Svartmocka (O), torrskorpelera (□).

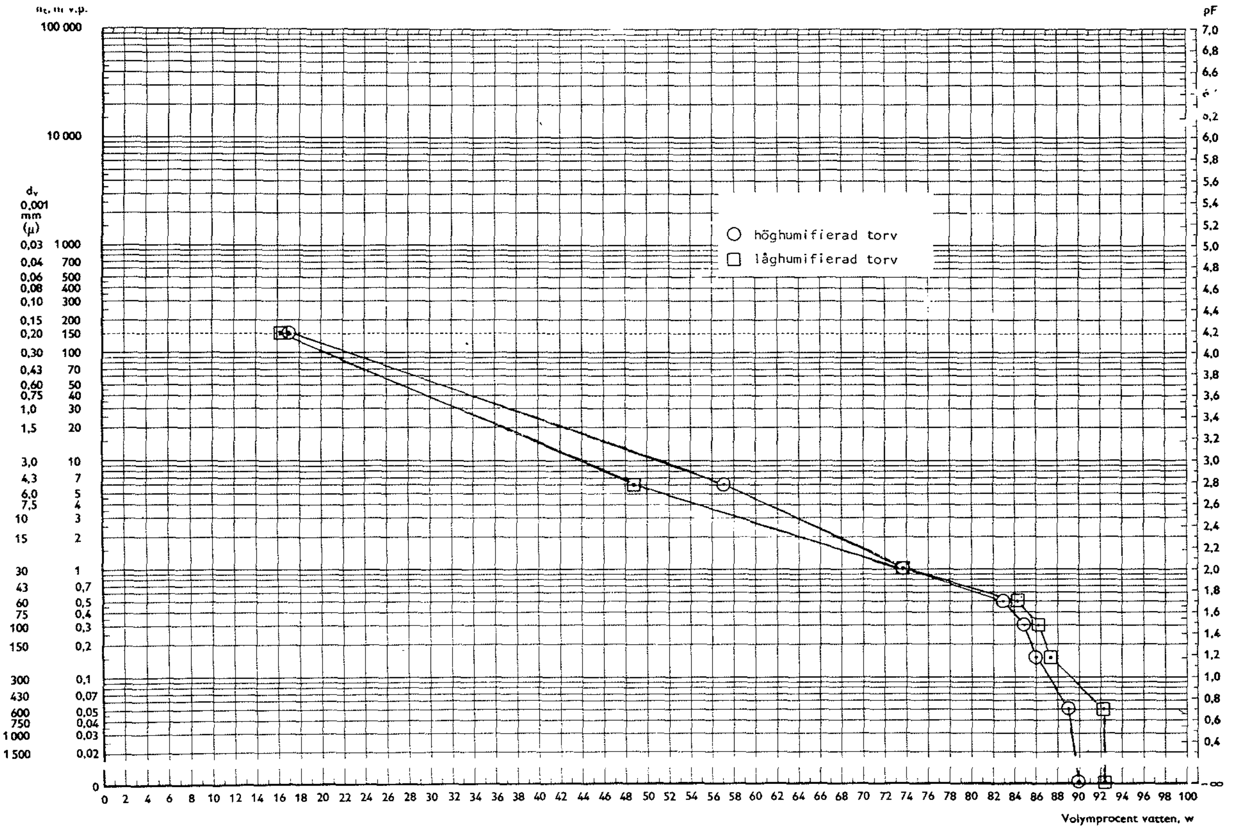


Fig. 8. High (O) and low (□) humified peat

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