Migration of aqueous acetone and KCl through E-Kaolin: minidrum centrifuge test CBLC1

by

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1. Introduction

The objective of the test was the measurement of migration profiles for two different contaminants simultaneously leaching through a clay layer due to a downward hydraulic gradient and to centrifuge acceleration. It was expected that density differences between the contaminants would result in different peak positions in the respective profiles.

The test was run in the Mini-drum Mark II centrifuge, using the clay model previously prepared and consolidated by Hugh Barker. The mini-drum centrifuge is shown schematically in Figure 1, and is described in Schofield [1992, 1994]. The test procedures roughly followed the same steps reported by Evans et *al.* [1994] and Evans [1995], but in a very simplified version.

Acetone and potassium chloride were selected to prepare the contaminant solution to be leached into the clay. These compounds are readily available and are simply analysed for. Another advantage was that this gives one organic and one inorganic contaminant to be traced through the clay layer.

The results obtained were not very satisfactory, and can be reasonably explained by a series of factors which are listed and discussed at the end of this report. Suggestions for further improvements are also presented.

2. Testing procedure

2.1 Materials

The clay was an E-grade Spestone Kaolin previously consolidated at a maximum centrifuge acceleration of 150g, with a one week time interval between the end of the previous consolidation and the beginning of this contaminant migration test. Ordinary tap water was used during the sample's preparation and consolidation.

The contaminant solution contained 2% acetone and 5·5mg/L KC1 dissolved in deionised water.

2.2 Test conditions

The model used is reproduced schematically in Figure 2. The value of 150g reported herein refers to centrifuge acceleration at the base of the model, which was at a radius of 370mm from the centrifuge axis. The centrifuge acceleration at the surface of the model was 115g, approximately. In order to maintain a downward hydraulic gradient throughout the test, the liquid surface was kept between five and ten millimetres above the upper clay surface at all times and the drain in the base sand layer was open.

2.3 Sequence of operations during test

Test CBLC1 was conducted on Wednesday 21st. June 1995. The model was reconsolidated at 150g for 3 hours 30 minutes, keeping the water pond surface 10mm above the clay surface. Ordinary tap water was used. The centrifuge was then slowed down to dead stop to dump the ponded liquid, which was replaced by the contaminant solution and the centrifuge run back up to 150g. This speed was maintained for 2 hours 45 minutes, keeping the contaminant pond surface 10mm above the clay surface. The same procedure was adopted to replace the contaminant solution by clean water again, and the centrifuge run for another 1 hour and 50 minutes to simulate partial clean-up due to leaching, using ordinary tap water.

2.4 Sampling

A special sampling device was constructed to take clay samples by skimming off layers lmm thick for later analysis. This profiler was based on the design previously developed for the centrifuge work of Evans [1995]. Figure 3 presents a schematic of the sampling procedure adopted.

Forty-five clay samples were taken at the end of the test, stored in plastic bottles, and taken to the laboratory. Sampling stopped at a model depth of 45mm, which prior calculations based on the seepage rate at the end of consolidation indicated should be nearly twice the advected distance. Analysis started the next morning, and some reduction in the acetone concentrations due to overnight evaporation was expected.

3.   Laboratory analysis

3.1 Moisture content

Before starting the pore water extraction, about 10 grammes was taken from each sample for moisture content measurements. The profile thus obtained should be representative of the model moisture contant versus depth profile itself. After extracting the pore water of all the samples, some of the samples were selected to also

measure the final moisture content, in order to estimate how much water was actually being obtained.

3.2 Pore water extraction procedure

Pore water was extracted from the clay samples by a double sequential centrifuge procedure: clay samples were first centrifuged at between 1600 and 1900rpm in a benchtop laboratory centrifuge, and the supernatant was then centrifuged separately in glass test tubes at 2000rpm to obtain clear water. Following this routine procedure resulted in about 5ml of pore water being extracted from each clay sample.

The sequence of extractions is summarised in Table 1.

3.3 Chemical analysis

The acetone concentration was calculated from the UV absorbance, measured with a Unicam 8620 spectrophotometer fitted with automatic cell filling. The UV spectrum of acetone in water shows a small maximum value at 268nm. Since it is always preferable to measure on or near a peak, this wavelength was used for concentration measurenments. The calibration was linear up to 0·5% (5000 ppm).

After centrifuge extraction of the pore water from the clay samples, the absorbance of the pore fluid at 268nm was used to calculate the acetone concentration. A solution of potassium chloride solution was checked for interference at this wavelength: only a very low absorbance was found (104 mg/litre KCl solution gave 0.013 AU). The typical repeatability of a pore fluid sample was +/- 2.3%.

The potassium concentration of the pore fluid was measured using a Unicam 929 atomic absorption spectrophotometer. Conditions were: acetylene/air flame, wavelength 766·5nm. To keep the analysis in the linear range of the spectrophotometer, it was necessary to dilute some of the samples of the pore fluid.

4. Results
4.1 General comments

According to the scaling laws of centrifuge modelling, the model tested corresponded to a theoretical prototype of a normally consolidated clay layer twelve metres thick:

$$\frac{l_p}{l_m} = \frac{1}{N} = \frac{1}{150}$$
$$\Rightarrow \quad l_p = 150 l, = 150 \times 0\cdot 08\,\mathrm{m} = 12\,\mathrm{m}$$

where l_m is the a length at model scale, l_p is the corresponding length in the prototype and N is the centrifuge scale factor for distance. Each lmm thick sample therefore

corresponds to a prototype sample 0·15m thick, and the 45mm total sampling depth into the model clay corresponds to cutting 6·75m into the prototype clay layer.

The scale factor for time is higher, at N^2, and the correspondance between model and prototype durations for the different stages is presented in **Table 2.**

The advance of contaminants through the clay does not stop when the contaminant solution is replaced by clean water. Since the hydraulic gradient through the sample was kept constant, both advection and dispersion processes continue during the clean up stage. What happens is a variation in the concentration gradient due to dispersion and a dilution effect behind the advancing contaminant front due to the movement of clean water through the clay by seepage. The results should then be interpreted for the whole period of time after consolidation (11 years, 9 months 12 days), considering the two stages:

1. Dispersion under a constant concentration gradient plus advection under the applied hydraulic gradient (7 years 23 days);
2. Dispersion under variable concentration gradient plus advection under the same hydraulic gradient (4 years 8 months 19 days).

The hydraulic gradient applied in the test was $i = N \times \Delta l/h = 150 \times 90/80 = 169$.

According to the control measurements taken during the test, pond liquid was going into the model clay at an average flow velocity of 10mm/hr., so the Darcy velocity $v = 2·78 \times 10^{-4}$ cm/s. This indicates a permeability coefficient $k = 1·64 \times 10^{-6}$ cm/s, a quite reasonable value for kaolin.

In the prototype, the test conditions correspond to a downward hydraulic gradient of 1.13 and a Darcy velocity of 1.85×10^{-6} cm/s. The mean moisture content is 36%, which indicates that the pore fluid velocity $\bar{v}$ is 3.79×10^{-6} cm/s. The seepage velocity in the sand layer at the base, v_b, will be a function of the permeability of the sand and the thickness of the layer.

4.2 Clay sampling procedure

The sampling procedure was very satisfactory for the upper layers of clay, but during the skimming of the deeper samples some clay from the sides of the excavated trench was also removed. This resulted in a small amount of cross-contamination.

4.3 Moisture content versus depth profile

Table 3 reproduces the data from moisture content measurements on samples collected from the model clay, and Figure 4 the moisture content versus depth profile obtained. The result are representative of a normally consolidated clay profile, with moisture content decreasing with depth as effective stress increases.

The previous consolidation history of this clay layer was not available at the time this report was written, but no pock marks were observed on the surface of the model at the end of the test and the results altogether seem quite satisfactory.

4.4 Contaminant profiles

The loss of acetone due to evaporation appears to have been greater than expected. These losses occur because it was very time consuming to extract the pore fluid from 45 samples, and because there were losses from the clay sample containers. This may have been through diffusion through the plastic containers, or via the screw top lid. The concentrations were significantly higher in the analyses done in the clay after the centrifuge run.

Table 4 reproduces the data from the acetone and the potassium determinations. The dilution factors for the potassium analyses are also shown. Where repeat measurements were taken, these are shown separately at the end of the table. The table headings show the number of days after the test on which the analyses were done. In the potassium dilution column, 1 indicates an undiluted sample.

Figure 5 presents the final profile for acetone and Figure 6 that for potassium. Acetone presented many problems relating to evaporation after sampling and cross-contamination during the sampling procedure. Potassium measurements were affected by the high background concentration of potassium in tap water, by contamination of the deionised water used for pore water sample dilution during the first measurements, and also probably by cross-contamination during the sampling procedure. The reasons for these statements are discussed below.

Six of the pore water samples were extracted in the first two days after the test: samples #3, #10, #13, #20, #30, and #35(a). Four of these were analysed in the same week for acetone: samples #3, #13, #30 and #35(a), and are indicated with different symbols on Figure 5. The other samples remained in the laboratory over the weekend, and extraction continued the next Monday. The plot clearly shows the significant evaporation loss that occurred in the first few days after the end of the centrifuge test, which probably not only reduced the overall acetone concentration but also smoothed down the profile. During sampling it was noticed that samples #35(a) through #39 had a strong acetone smell, and the first four samples analysed indicate a similar trend.

For the rest of the samples, apart from small local variations, there is a trend of increasing acetone concentrations up to sample #34. From then on the scattering is so significant that it becomes impossible to explain the results obtained. The only explanation which seems reasonable for that behaviour is cross-contamination during sampling, since those were the last and deepest smples to be skimmed off, and control of what was actually being collected was becoming increasingly difficult.

The pore water extraction was not important for potassium analysis, but some other problems did occur. The contaminant source solution was made up with 5·5mg/L KCl in deionised water, but it was later discovered that the tap water used in the model consolidation and clean-up stages itself had a background concentration equivalent to about 5mg/L KCl. Another problem that arose during the laboratory analysis was dilustion of pore water samples in deionised water contaminated with potassium chloride because of inadequate prior cleaning of the deionised water storage container. The analyses had to be repeated, but some samples were no longer available. What cannot be explained is the magnitude of the potassium concentrations in the last deep samples, as they are all high above 10mg/L, putting them above the maximum source conetration.

Figure 6 shows a continuous trend of increasing potassium concetration towards sample #45, which cannot be disregarded despite all the problems described. It appears that the potassium concentration peak has been missed because of the sampling depth limit adopted. If this is correct, then the acetone concentration peak actually occurred around 10mm above the probable potassium peak, which would correspond to a difference of 1·50m in the prototype. Since so many problems were encountered in this test, it is advisable to repeat it before making definite conclusions about the subject.

4.5   Suggestions for improvement

1. Improve the design of the samping device to prevent cross-contamination of samples, and avoid sampling too close to the centrifuge walls.

2. Select another organic compound less volatile than acetone, as cetrifuge testing and sampling procedures take a long time and significant evaporation losses occur.

3. Improve pore water extraction procedures, or use a more powerful laboratory centrifuge, or create a special squeezing device to extract pore water from the clay sample uder high pressure. This is particularly important when there is a significant variation in moisture content through the clay layer or when dealing with low concentrations.

4. Keep good control of background concentrations of the materials used during all stages of the test.

Appendix 1 • References

1. Evans, D. C. [1995]: "Contaminant migration through intact and damaged clay liners", Ph.D. thesis, Department of Engineering, University of Cambridge.

2. Evans, D. C., Savvidou, C. and Schofield, A. N. [1994]: "Contaminant migration through clay in a mini-drum centrifuge", *Proceedings of the International Conference Centrifuge* 94, held in Singapore 31st. August to 2nd September 1994, A. A. Balkema, pp. 381-386.

3. Schofield, A. N. [1992,1994]: UK International Patent application under the Patent Co-operation Treaty.

Appendix 2 · Tables

Table 1 — Pore water extraction sequence

Date	Samples
Thursday 22 June 95	#10, #20, #30
Friday 23 June 95	#3, #13, #35(a)
Monday 26 June 95	#1, #2, #4, #5, #6, #7, #8, #9, #11
Tuesday 27 June 95	#12, #14, #15, #16, #17, #18, #19, #21, #22, #23, #24, #25, #26, #27, #28, #29
Wednesday 28 June 95	#31, #32, #33, #34, #35(b), #37, #38, #39, #40, #41
Thursday 29 June 95	#42, #43, #44, #45

Table 2 — Model and prototype durations

Stage	Model duration	Prototype duration
Consolidation	3 hours 30 minutes	9 years
Leaching	2 hours 45 minutes	7 years 23 days
Clean up	1 hour 50 minutes	4 years 8 months 19 days

Tablt 3 — Sample moisture contents

Sample no.	Cont. (g)	Cont. + wet soil (g)	Cont. + dry soil (g)	Water (g)	Total weight (g)	Water content (%)	Sample depth (mm)
1	48.00	54.07	5 1.50	2.57	6.07	42.34	O-1
2	47.02	56.65	52.87	3.78	9·63	39·25	1-2
3	47.07	57.68	53.56	4.12	10·61	38.83	2-3
4	48·00	58.15	54.27	3.88	10·15	38.23	3-4
5	47·73	57.26	53.68	3·58	9·53	37·57	4-5
6	47·92	57·33	53.72	3.61	9·41	38.36	5-6
7	47.04	57.08	53·29	3·79	10.04	37.75	6-7
8	47.88	58.08	54.23	3.86	10·21	37.8 1	7-8
9	47.86	59·31	55·01	4·30	11·45	37·55	8-9
1 0	—	—	—	—	—	—	9-10
11	47.73	58.9	54·75	4·15	11·17	37.15	10–11
12	48.04	59·68	55·35	4·33	11.64	37.2	11-12
13	47.63	57.85	54·09	3.76	10·22	36.79	12-13
1 4	47.8 1	56·5	53·32	3.18	8.69	36.59	13-14

15	47·81	57.64	54.05	3·59	9·83	36.52	14-15
16	47.61	58.34	5444	3·90	10·73	36.35	15-16
17	47.91	57·70	54.12	3.58	9·79	36.57	1617
18	48.19	59·11	55·18	3·93	10.92	35·99	17-18
19	47.65	58.88	54.86	4.02	11·23	35·80	18-19
20	—	—	—	—	—	—	19-20
21	46.85	56.52	53·09	3.43	9·67	35·47	20-21
22	48·04	59.62	55·53	4·09	11·58	35.32	2 1-22
23	47.77	57.24	54.00	3.24	9·47	34.2 1	22-23
24	47·75	57.6 1	54.3 1	3.30	9.86	33.47	23-24
25	47.76	57·54	54.25	3·29	9·78	33.64	24-25
26	47·04	57.73	54.13	3.60	10·69	33.68	25-26
27	47.85	57.52	54.22	3·30	9·67	34.13	26-27
28	47.86	58.19	54.6 1	3.58	10·33	34.66	27-28
29	48.14	59·14	55.39	3·75	11·00	34·09	28-29
30	—	—	—	—	—	—	29-30
31	48.17	58.5 1	54·95	3.56	10.34	34·43	30-31
32	47·02	57.78	54·07	3.71	10·76	34·48	3 1-32
33	47·00	57.22	53·71	3.51	10·22	34·34	32-33
34	47·97	60.36	56.11	4.25	12.39	34·30	33-34
35(a)	47.09	57.86	54·20	3.66	10·77	33·98	34-36
35(b)	46·89	56.26	53·06	3.20	9·37	34.15	34-36
37	47.87	58·29	54.78	3·51	10.42	33·69	36-37
38	47.77	58.62	54·93	3·69	10·85	34·01	37-38
39	46·97	59.21	55.08	4·13	12·24	33.74	38-39
40*	47·30	57·89	54.27	3.62	10·59	34.18	39-40
41	46·94	57·34	53.83	3·51	10·40	33·70	40-41
42	47.52	57.22	53·94	3.28	9·70	33·81	41-42
43	47·35	57.56	54.14	3.42	10·21	33·50	42-43
44	48·03	58.14	54.75	3·39	10·11	33·53	43-44
45	47·17	58.83	54.93	3·90	11·66	33·45	44—45

* After being centrifuged in the laboratory and taken out of the bottle

Table 4 — Results of chemical analysis

Sample no.	Acetone conc. days 5–8 (mg/L)	Acetone conc. day 1 (mg/L)	Potassium dilution	Potassium conc. day 12 (mg/L)	Potassium conc. day 13 (mg/L)	Sample depth (mm)
1	—	—	1	—	—	O-l
2	139·53	—	1	—	8.253	l-2
3	—	319·45	1	—	8.635	2-3
4	168.91	—	1	—	7.576	3-4
5	198.28	—	1	—	7.547	4-5
6	241.12	—	1	—	7·590	5-6
7	261.93	—	1	—	7·733	6-7
8	292.53	—	1	—	7.380	7-8
9	365.96	—	1	—	7.473	8-9
10	555.68	—	1	—	11·140	9-10
11	485.9 1	—	1	—	8·051	10–11
12	421.04	—	1	—	8.126	11-12
13	—	911·85	1	—	9.442	12-13
14	37 8.20	—	1	—	8.935	13-14
15	439.40	—	1	—	10.060	14-15
16	547·11	—	1	—	10·590	15-16
17	466.33	—	1	—	11·436	16-17
18	489.58	—	1	—	11·656	17-18
19	537.32	—	1	—	10·324	18-19
20	563·02	—	1	—	10·782	19-20
21	560.57	—	1	—	9·550	20-2 1
22	505·50	—	1	—	10.634	21-22
23	561·80	—	1	—	11.866	22-23
24	881.25	—	1	—	11·898	23-24
25	1059.95	—	2	13.372	11.738	24-25
26	844.53	—	3	13·875	11·469	25-26
27	784.56	—	3	16·119	12·840	26-27
28	908·18	—	3	17·643	13·095	27-28
29	947·35	—	3	18.687	14·505	28-29
30	—	2030·55	3	18.876	15.435	29-30
31	1061·17	—	3	18·444	—	30–31
32	949·79	—	3	19.398	—	3 l-32
33	1287.61	—	6	24.333	—	32-33

3 4	1488·34	—	6	26.692	—	33-34
35(a)	—	2594·80	6	25.692	—	34-36
35(b)	626.67	—	6	28.272	—	34-36
37	456.54	—	6	33·180	—	36-37
38	1342.68	—	9	39·708	—	37-38
39	1434.48	—	6	48.792	—	38-39
4 0	1024·45	—	6	39.828	—	39-40
41	1451.52	—	6	39.564	—	40—41
4 2	599.74	—	6	42.654	—	4 1-4 2
43	488.36	—	6	43.812	—	42-43
4 4	903·28	—	6	43.842	—	43-44
4 5	865.34	—	6	45·822	—	44-45
11	408.80	—	—	—	—	10-l 1
16	—	—	1	—	10·892	15-16
32	941·23	—	—	—	—	3 l-32
35(a)	550·78	—	—	—	—	34-36
3 7	45 1.64	—	—	—	I -	36-37
3 9	1401.43	—	6	49.476	-	38-39
4 0	959.58	—	—	—	—	39-40
41	1373.28	—	—	—	—	40—41
4 2	531.20	—	—	—	—	4 1-4 2
43	481.59	—	—	—	—	42—43
4 4	855·55	—	—	—	—	43-44
4 5	790.68	—	—	—	—	44-45

Appendix 3 — Figures

Figure 1 — Elevation of Mark II mini-drum centrifuge with drive shaft vertical
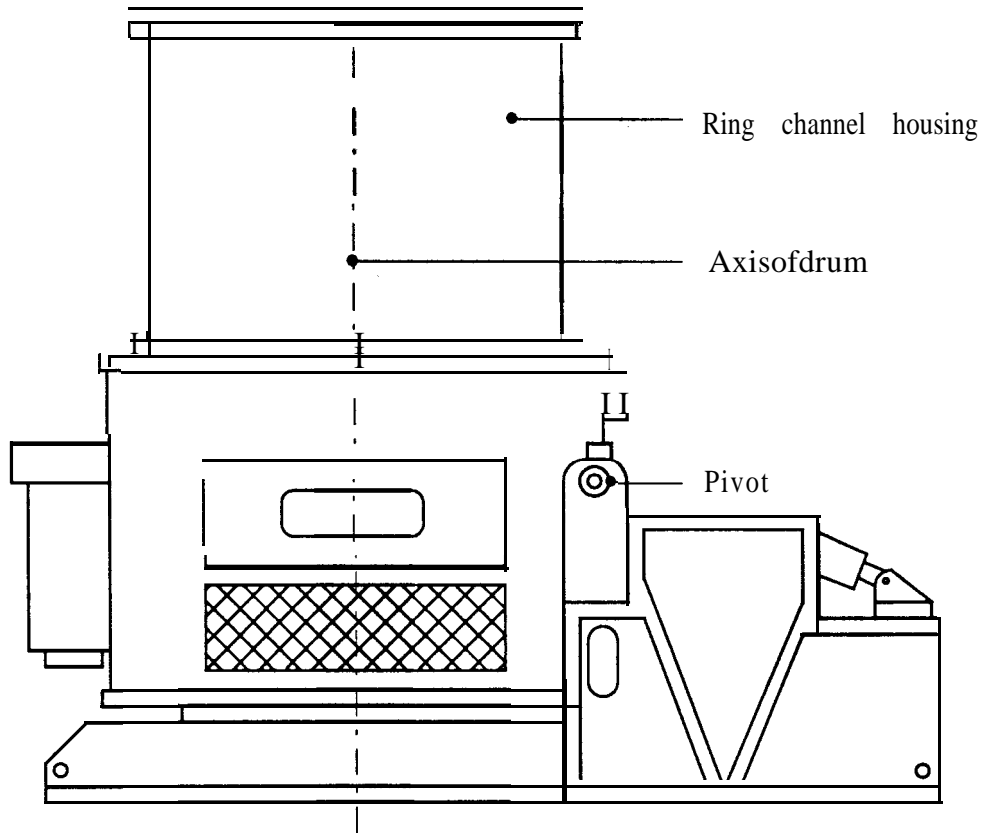
Ring channel housing

Axisofdrum

Pivot

Figure 2 — Mini-drum model schematic

10 mm

80 mm

$\bar{v}$

Ng

v_b

W.L.

W.L.

Free-draining
sand layer

Clay
(E-grade kaolin)

Centrifuge
walls
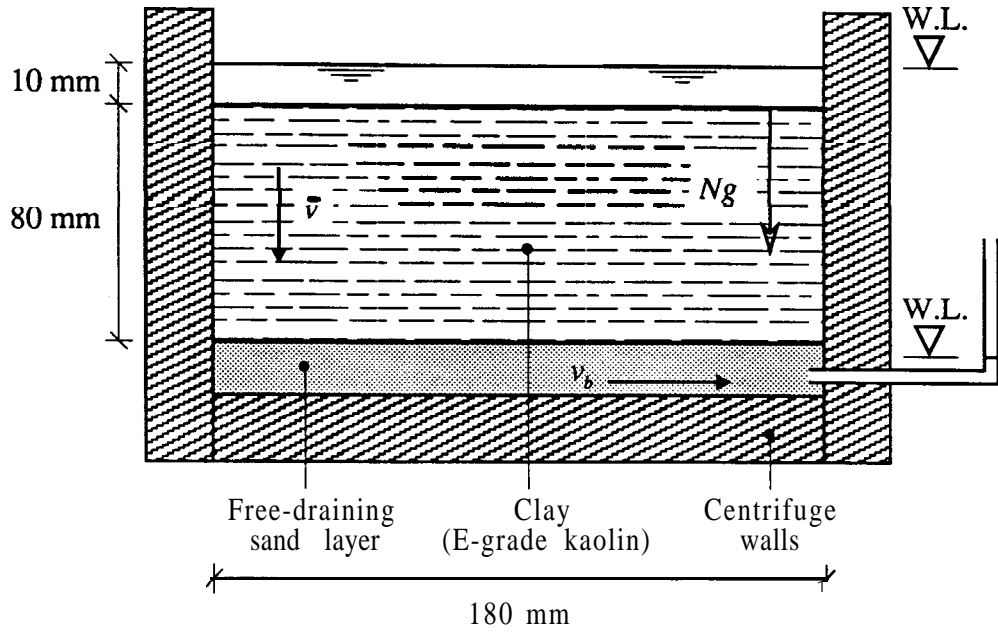
180 mm

Figure 3   Sampling tool schematic

10 mm

50 mm

Cutter

Side view

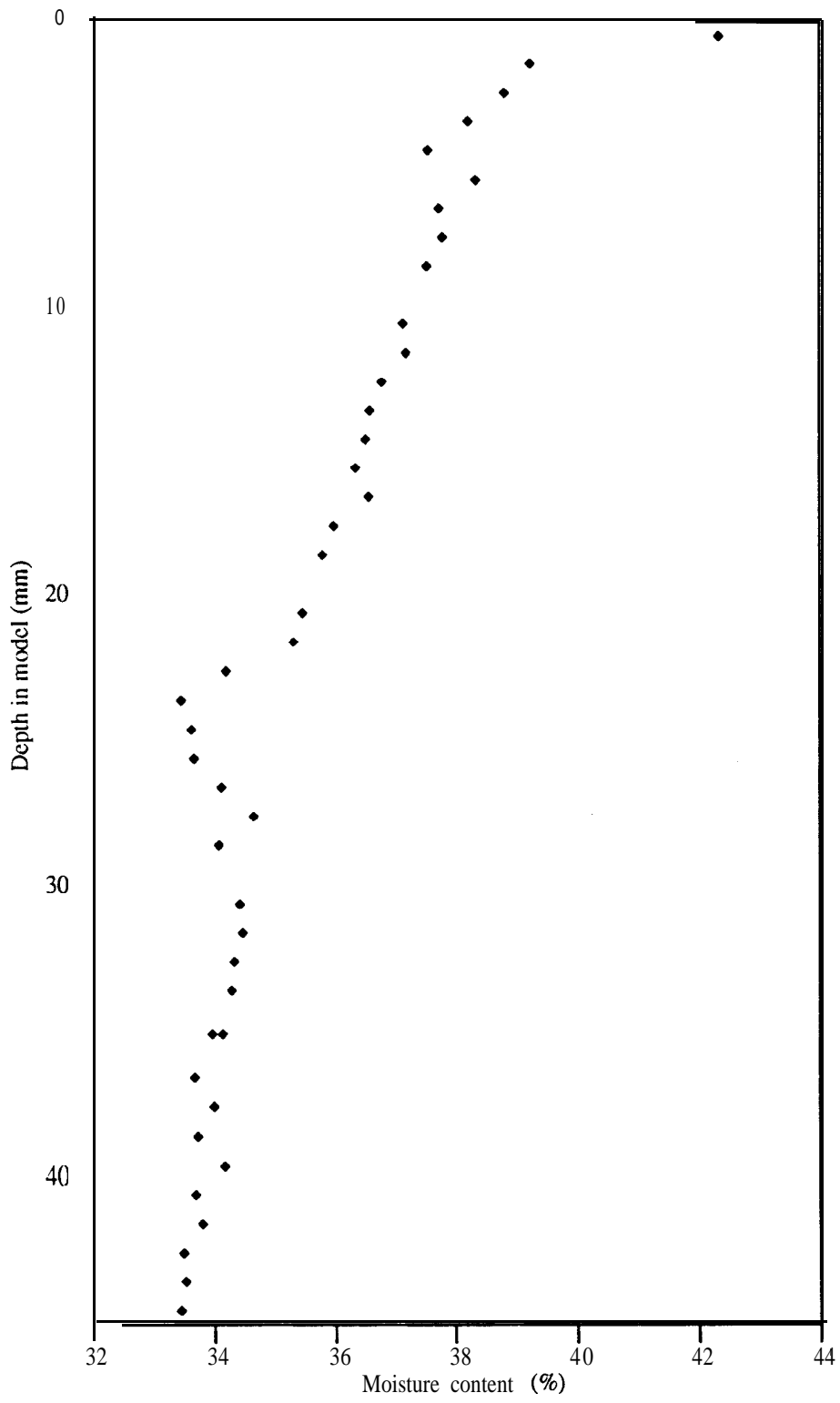Plan view
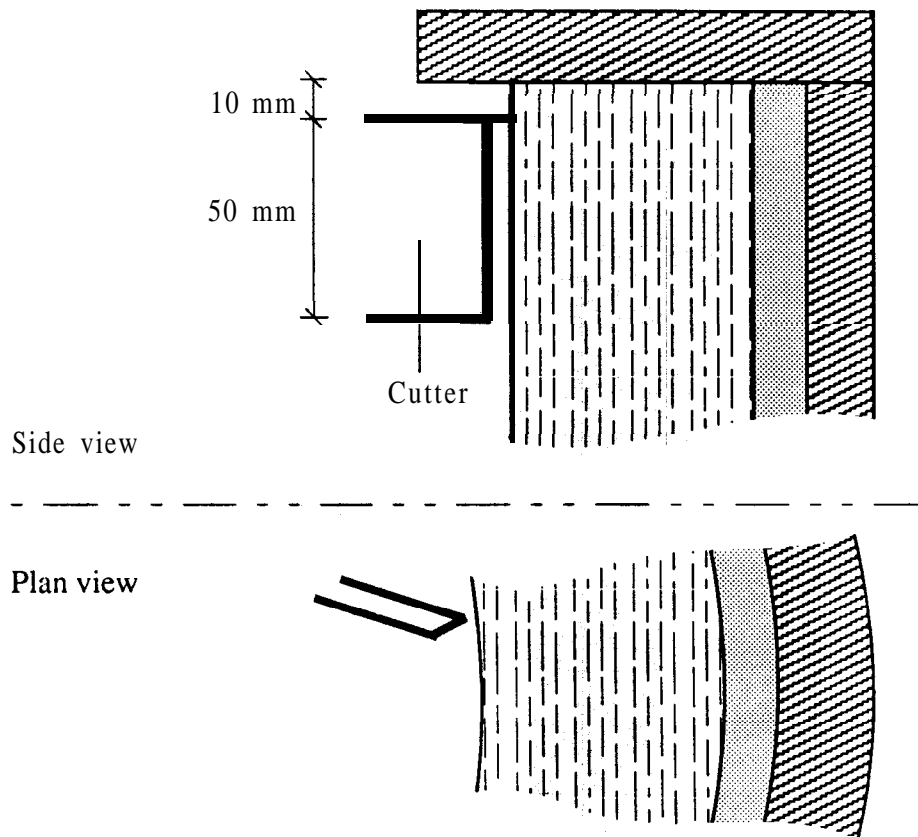
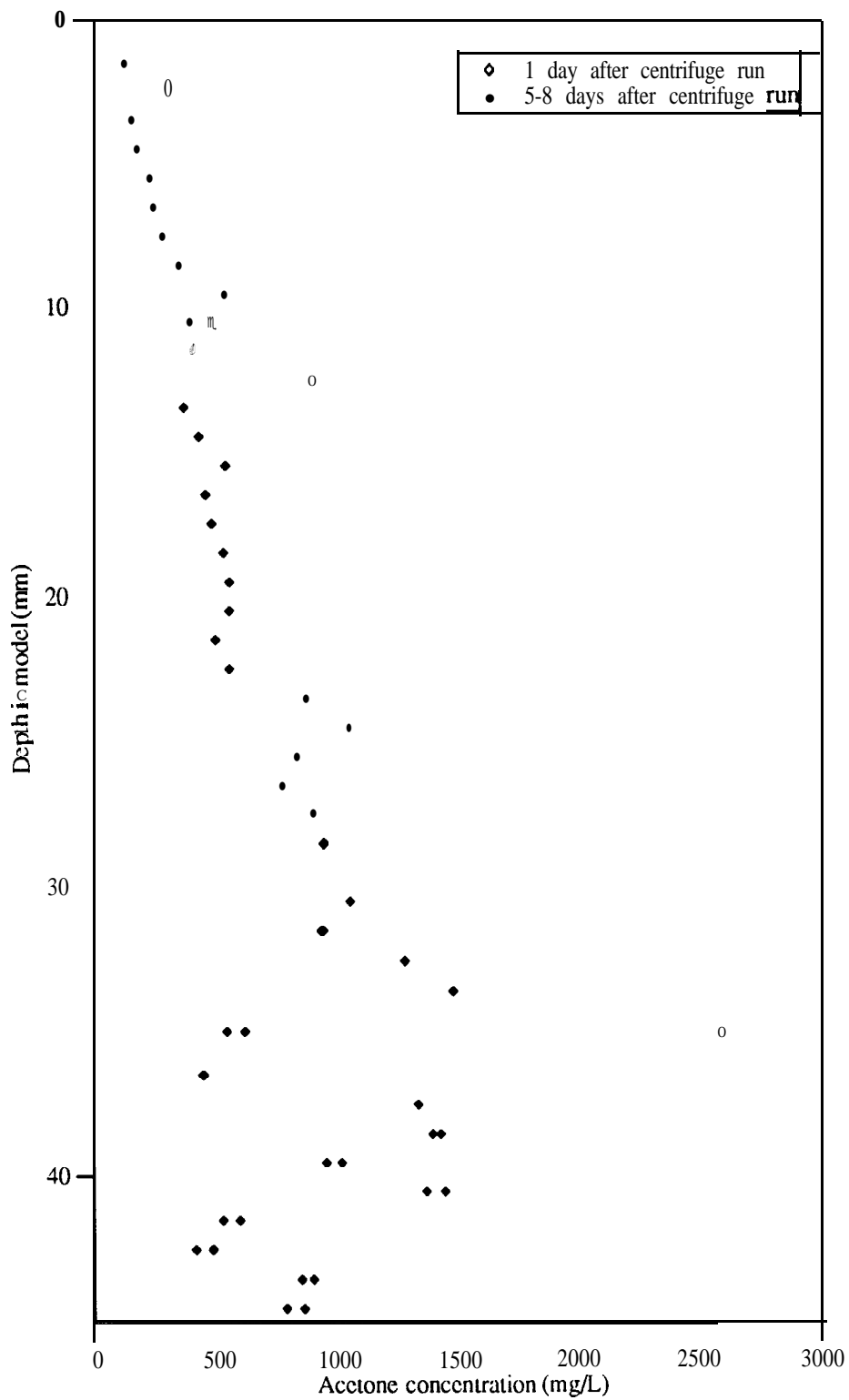Figure 4 — Profile of sample moisture contents

Figure 5 — Profile of acetone concentrations

Figure 6 — Profile of potassium concentrations