Laboratory permeability measurements with Mercia Mudstone

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INTRODUCTION

As the environmental regulator, the Environment Agency insists on a strict standard of construction quality for lining and capping environmental protection systems at landfill sites. Current requirements for mineral liners dictate permeability testing in accordance with the British Standard constant head triaxial test (BS 1377 Part 6, Method 6) (BS test). In this test method the saturation, consolidation and permeability stages are carried out as distinct and sequential operations. However, there have been proposals from the waste industry to adopt an Accelerated Permeability Test (AP test) as an alternative means of assessing permeabilities. The Agency commissioned Murray Rix Ltd to carry out research to investigate the possible use of the AP test, where the consolidation, saturation and permeability stages are carried out as one, which might speed up the availability of results.

The brief was to investigate the AP test methodology and compare the results from controlled laboratory tests using the two methods. The paper presents results of tests carried out on one of the materials examined, Mercia Mudstone (MM). The test data presented includes the results of measurements of volumetric (density) and moisture content changes throughout the permeability tests. Permeability test results are presented for samples prepared at water contents and densities likely to be used in actual construction. Interesting conclusions may be drawn with respect to the significance of effective stress and hydraulic gradient on the permeability values and soil behaviour.

MATERIAL PROPERTIES

At source the MM material comprised firm to stiff friable red brown clay and very weak fragmented mudstone (gravel size). This was screened to remove/break down material >10mm in size. X-Ray Defraction indicated the clay mineralogy to comprise predominately chlorite and muscovite. The properties of the material following screening are outlined in Table 1.

TABLE 1 - Material Properties

					Particle Size Distribution				
Material	**LL**	**PL**	**PI**	**Classification**	**Clay (%)**	**Silt (%)**	**Sand (%)**	**Gravel (%)**	**Activity**
MM	34	20	14	CL	25	26	43	6	0.56
					34	23	41	2	0.41

The initial gradation is based on careful analyses with every effort taken to avoid breaking down of the coarser fractions and gives a picture of the gradation prior to specimen preparation and testing. The second grading distribution is based on normal BS testing techniques where the weaker mudstone fractions are broken down during the drying and sieving process. Careful grading analyses after specimen preparation and permeability testing

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indicated breaking down of the coarser fractions to an overall gradation intermediate between the ranges shown in Table 1.

PERMEABILITY TEST PROCEDURES

The test procedures were designed to provide information on the specimen condition throughout the permeability tests. The volume and moisture content changes necessary to determine the foregoing were based on the initial condition of the specimens prior to insertion in the triaxial cell. The test methodologies suggested that there were likely to be greater errors resulting from calculations based on end of test conditions as a result of uptake of water by the specimens, and the release of air from solution, on reduction in cell pressure. All tests were on recompacted laboratory prepared specimens of nominal 100mm diameter and 100mm length to minimise scale effects (Mitchell and Younger, 1967). As illustrated in Fig.1, volume change indicators A, B and C were included on the top and bottom back-pressure lines, and the cell pressure line, respectively. Indicators A and B allowed for measurement of the water entering and leaving the specimen while C allowed measurements of volume change of the specimen during each stage, after allowing for calibrated cell expansion. A pore water pressure transducer was incorporated in the pore pressure line at the base of the specimens.

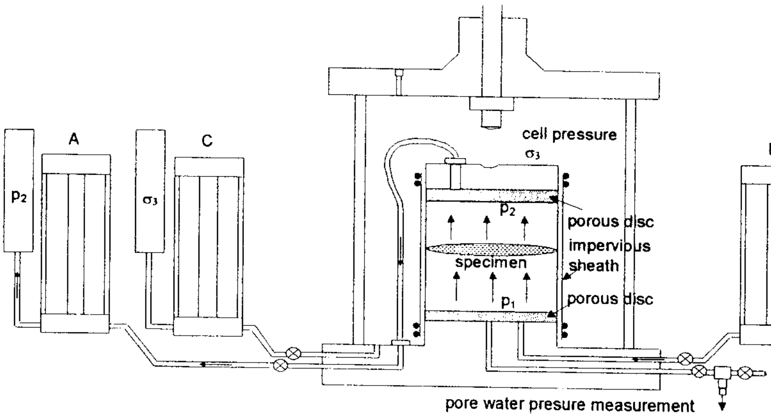

Fig. 1 Triaxial Cell Set-up

The BS Test

BS1377:1990 allows for alternative methods of saturation and consolidation prior to the permeability stage in the constant head test. In addition, discussions with the various laboratories consulted indicated different interpretations of the test procedure primarily to reduce on testing times. The following procedures were adopted in the permeability tests:

Saturation Stage – Alternating increments of cell pressure and back-pressure were applied while maintaining a small positive effective stress. Back-pressure was applied to the top of the specimen only and pore water pressures recorded at the base. At each level of total stress, B values were determined. A value of $B \geq 0.95$ was taken as indicative of adequate saturation.
Consolidation Stage – The procedure adopted was to allow drainage upwards while recording the pore water pressure at the base. Under these conditions the requirement for at least 95% dissipation of excess pore water pressure was ensured. Throughout the BS tests reported herein, an average effective stress of 187.5kPa was used as in the AP tests.

Permeability Stage – BS1377:1990 allows for permeability measurements under vertical upwards or downwards flow. In the tests undertaken, the hydraulic gradient was applied to achieve upward flow as adopted in most commercial laboratories. Though the average effective stress was maintained constant, the BS tests comprised two stages corresponding to an increase in the hydraulic gradient. A hydraulic gradient of 30 was applied in Stage 1 of the BS procedure but subsequently increased in Stage 2 to that of the AP test of 125[1]. An example of cumulative flow against time in a BS test is given in Fig.2.

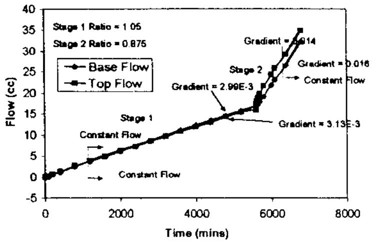

Fig.2 Cumulative Flow against Time – Test Series 1, MM(BS1)

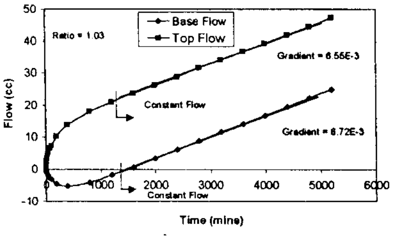

Fig.3 Cumulative Flow against Time - Test Series 1, MM(AP1)

The AP Test

Following consultations with a large number of commercial laboratories, a consensus was reached to adopt imposed cell and back-pressures as detailed in Table 2.

Combined Saturation, Consolidation and Permeability Stages – The test uses hydraulic gradients and effective stresses in excess of those normally employed in the BS test. As no separate saturation or consolidation stages are employed, concerns have been raised on the influence of the test methodology on the measured permeability values and the degree of saturation of the specimens at the end of the tests. This is addressed in the following. An example of cumulative flow against time in an AP test is given in Fig.3.

TEST SERIES AND SPECIMEN IDENTIFICATION

Permeability tests were carried out on paired BS and AP test specimens prepared to initially similar conditions. As an example of the full specimen designation used in Table 2: MM(AP3) defines the material as Mercia Mudstone (MM) and the test as Accelerated Permeability Test number 3 (AP3 in Fig.4). Though the research programme included for three test series, only Test Series 1 and 3 were carried out on MM material and are outlined below:

Test Series 1 - Tests at 2 different target moisture contents and target air voids contents of 5% and 10%. The lower moisture content was the mean optimum from BS (2.5kg) Light Hammer Compaction tests and the higher moisture contents corresponded to an undrained shear strength of approximately 50kPa (BS1 to 4 and AP1 to 4 of Fig.4).

Test Series 3 - Tests were carried out at one target moisture content and two target air voids contents of 5% and 10%. The moisture content was the optimum from BS (4.5kg) Heavy Hammer compaction tests (BS5 and 6 and AP5 and 6 of Fig.4).

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[1] In the BS test the average effective stress is specified and the hydraulic gradient is adjusted to achieve measurable flow. In the AP test both the cell pressure and top and bottom back-pressures, thus the hydraulic gradient and average effective stress, are specified.

Though the preparation moisture contents were in part determined from BS 2.5kg and 4.5kg compaction tests, the specimens were prepared by static compaction to the required dry densities as this was felt to provide a more uniform test specimen.

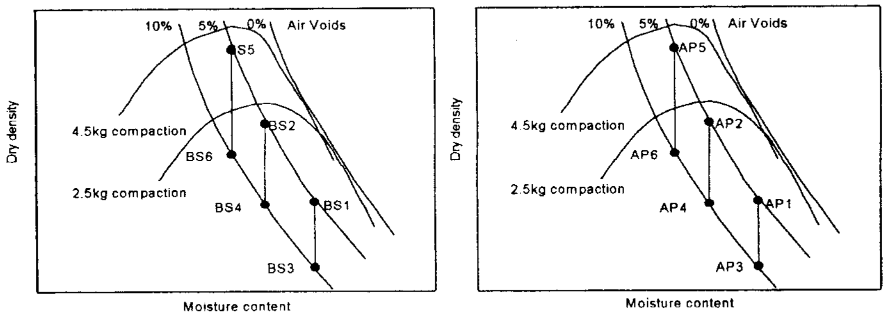

Fig. 4 Specimen Identification

DISCUSSION OF RESULTS

Examples of the plots of variation in moisture content against dry density in the paired BS and AP tests are presented in Figs 5 to 7.

TABLE 2 - Test Details and Results for MM Material

Test Series	Specimen Designation	Cell Press. (kPa)	Bottom Back Press. (kPa)	Top Back Press. (kPa)	Av. Consol. Press.[2] (kPa)	Hydraulic Gradient	Permeability (m/s)
1	MM(BS1) Stage 1	602.5	430	400	187.5	30	2.00E-10
	MM(BS1) Stage 2	650	525	400	187.5	125	2.10E-10
	MM(AP1)	550	425	300	187.5	125	1.05E-10
	MM(BS2) Stage 1	502.5	330	300	187.5	30	8.80E-10
	MM(BS2) Stage 2	550	425	300	187.5	125	1.30E-9
	MM(AP2)	550	425	300	187.5	125	4.00E-10
	MM(BS3) Stage 1	602.5	430	400	187.5	30	2.90E-10
	MM(BS3) Stage 2	650	525	400	187.5	125	2.60E-10
	MM(AP3)	550	425	300	187.5	125	1.40E-10
	MM(BS4) Stage 1	502.5	330	300	187.5	30	8.30E-10
	MM(BS4) Stage 2	550	425	300	187.5	125	1.20E-9
	MM(AP4)	550	425	300	187.5	125	1.30E-8
	MM(AP4)r[1]	550	425	300	187.5	125	8.80E-9
3	MM(BS5) Stage 1	552.5	380	350	187.5	30	4.20E-10
	MM(BS5) Stage 2	552.5	427.5	302.5	187.5	125	7.40E-10
	MM(AP5)	550	425	300	187.5	125	1.40E-8
	MM(BS6) Stage 1	752.5	580	550	187.5	30	1.20E-9
	MM(BS6) Stage 2	752.5	627.5	502.5	187.5	125	3.80E-9
	MM(AP6)	550	425	300	187.5	125	1.10E-7

[1] Repeat test

[2] Average consolidation pressure (average effective stress) is defined as the cell pressure less the mean of the top and bottom back-pressures.

Specimen Preparation

Those specimens which were prepared to the initially drier and more densely compact conditions, were notably less compact than the target values on extrusion from the compaction moulds. This applied particularly to the paired specimens MM(BS2) and MM(AP2), and MM(BS5) and MM(AP5), as shown in Figs 6 and 7. The density reduction may be attributed to an 'elastic' expansion of the low plasticity clay, which contain mudstone 'peds', on reduction in confining stress. Repeat compaction operations confirmed that this was a material response to the release of confining stress. On reduction in cell pressure and removal from the triaxial cell after permeability testing, specimens of MM material again experienced notable expansion.

Density and Moisture Content Variations during Testing

The dry density against moisture content paths in the BS tests are marked as A-B-C-D-E on Figs 5 to 7. In these tests, there was a very low effective stress (circa 10kPa) applied until the end of the saturation stage at C; A-B being the initial specimen response to opening the top back-pressure tap. All specimens are shown to increase in moisture content between A and C. The less compact, wetter specimens (e.g. Fig.5) exhibited an increase in dry density but the more heavily compact and drier specimens, (e.g. Fig.7), exhibited a rapid and large decrease in density. Specimen MM(BS2), (Fig.6), exhibited little volume change and presents an intermediate response between those of the other specimens. During the subsequent consolidation stage C-D, there was an increase in dry density of the specimens with the plots running parallel to the zero air-voids line. Following this, during the permeability stage D-E, only very small changes in moisture content and dry density occurred.

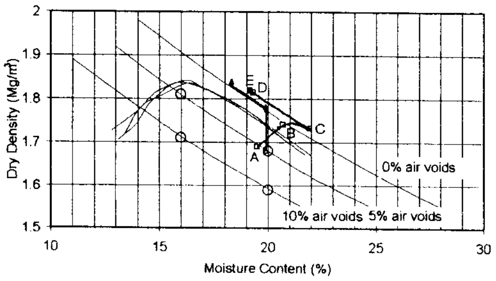

Fig.5 Dry Density/Water Content Paths– MM(BS1) and MM(AP1)

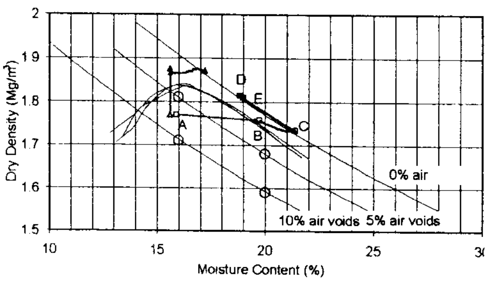

Fig.6 Dry Density/Water Content Paths– MM(BS2) and MM(AP2)

The behaviour during the AP tests contrasted with that during the BS tests. The wetter and less compact AP tests (e.g. Fig.5) exhibited a rapid compression to near-zero air voids under the initial application of the cell pressures of 550kPa. This was not the case for the drier and more compact specimens (e.g. Fig.7) where there was a gradual increase in moisture content at near-constant specimen volume as the tests proceeded. The swelling exhibited during the initial stages of the MM(BS5) and MM(BS6) tests did not occur in the paired AP tests where the effective stress (187.5kPa) was well above that of the BS tests initially.

The BS and AP tests followed distinctly different stress paths. At the end of permeability stage, the specimens were more compact in the AP tests even though the same average effective stress was adopted in the consolidation and permeability stages of the BS tests. Allowing the combined permeation and consolidation in the AP tests is considered to have facilitated migration of the finer particles into the voids between mudstone peds and a denser end condition for the specimens. In the staged BS tests, permeation took place only after consolidation and very little subsequent volume change occurred (movement of particles during permeation is likely to have been more restricted).

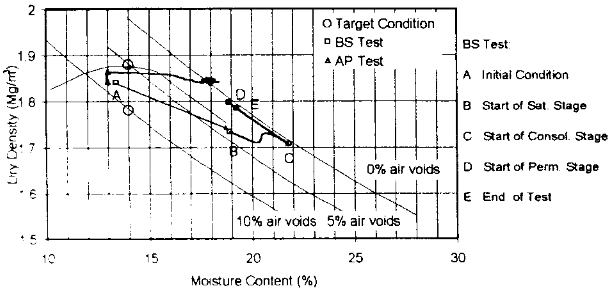

Fig.7 Dry Density against Moisture Content Paths – MM(BS5) and MM(AP5)

Of note is that at the end of both the BS and AP tests all specimens indicated near-saturated conditions based on determinations of air-voids contents. However, the B values for the AP test specimens were often around 0.9 after permeability testing. The relatively low B values are considered a consequence of the consolidated condition of the specimens.

Flow and Permeability Measurements

As illustrated in Table 2 and Fig.8, the permeabilities in tests MM(AP1), MM(AP2) and MM(AP3) were approximately half those of the paired BS tests. The plots are presented for Stage 1 of the BS tests where a hydraulic gradient of 30 was employed compared to a hydraulic gradient of 125 in the AP tests. As all specimens were shown to have been near-saturated, the lower permeabilities in these AP tests are considered primarily a consequence of the more compact state of the AP specimens.

The results of test MM(AP4), MM(AP5) and MM(AP6) indicate permeabilities one to two orders of magnitude (10 to 100 times) greater than in the paired BS tests. The AP test permeabilities were significantly greater than 1×10^{-9}m/s, the criterion often adopted as an upper limit to permeability for landfill sites, while the BS test permeabilities were generally less than this criterion. Establishing a reason for this and the significance to permeability testing of such soils is of the utmost importance in the design of landfills. The initial moisture content and density of the specimens is obviously important and influences the soil structure. The effective stress is considered the other major factor.

Influence of Soil Macro Structure

In the drier specimens, there is likely to have been a high degree of fissure continuity. This is consistent with the notable expansion of the more densely compact specimens on removal from the compaction mould. Under these conditions, discontinuities will have opened and pore water pressures will have reduced. It is estimated that suctions generally within the range 100 to 250kPa are likely to have been present on removal of samples from the compaction mould within the range of moisture contents of the tests. Subsequently, the BS test specimens MM(BS5) and MM(BS6) experienced a rapid and large increase in volume (reduction in dry density) with a concomitant increase in moisture content when the specimens were exposed to water in the triaxial cell. The low moisture content and fissured and desiccated structure would be conducive to a relatively rapid uptake of water particularly along discontinuities. At points of contact between saturated 'packets' the stabilising influence of suction will have been reduced resulting in propagation of fissures.

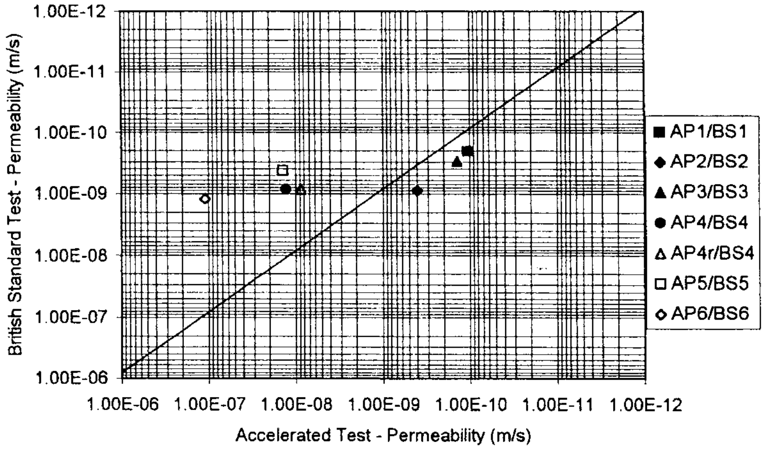

Fig.8 Comparison of AP and BS Permeability Measurements

Following the completion of the saturation stage, the subsequent consolidation stage will have resulted in closure of the fissures and healing (Fernandez and Quigley, 1990) of specimens. However, fissures will not have fully healed resulting in greater permeabilities in tests MM(BS4), MM(BS5) and MM(BS6) than obtained for the initially less compact specimens MM(BS1) and MM(BS3).

In the drier AP test specimens, the same process of expansion and fissure development on removal from the compaction mould may be inferred. However, there was not the low effective stress imposed as in the saturation stage of the BS tests. The plots of cumulative flow indicated uptake of water and positive pore water pressures of the order of 300kPa (roughly equivalent to the top back-pressure) as present on application of the elevated cell pressure. As there was no separate consolidation stage in the AP tests there is not thought to be the same degree of healing of fissures as in the paired BS tests resulting in greater permeabilities.

Influence of Effective Stress (and Hydraulic Gradient)

Boynton (1983) performed tests to illustrate the influence of effective stress on compacted clay. The average effective stresses varied between 14 and 103kPa. Where desiccation cracks were present the tests exhibited significantly greater permeability under low effective stress (well in excess of an order of magnitude greater) than under the higher effective stress. The influence on permeability of closing fissures by increasing effective stress is also evident from the results of Garcia-Bengochea et al (1979), Juang and Holtz (1986) and Murray et al (1996).

The influence of effective stress is not restricted to heavily fissured soils. Silver (1995) and Silver and Joseph (1999) concluded that the main impact on clay permeability is the structural changes in fabric due to effective stress induced deformations. This is compatible with the findings of other tests carried out as part of the research programme.

The influence of the hydraulic gradient, which is a measure of the rate of change of effective stress through a specimen, is less well appreciated. A considerable amount of evidence has been advanced to indicate that there is deviation from Darcy's law in fine-grained soils at low hydraulic gradients of less than about 6 (Mitchell and Younger, 1967). The deviation is likely to be influenced by the adsorbed double layer. There is also concern over elevated hydraulic gradients. It has been found experimentally that elevated hydraulic gradients can give rise to both increase (Schwartzendruber, 1969) and decrease (Mitchell and Younger, 1967) in permeability. Increase in permeability may be a result of mechanisms such as piping or hydraulic fracturing. Decrease in permeability appears to be a result of particle migration, causing clogging. Hird et al (1997) suggest from tests on colliery spoil that particle migration may give rise to both increase and decrease in permeability and that it is influenced by the hydraulic gradient. The direction of flow in permeability tests is likely to influence particle migration and may thus influence permeability measurements.

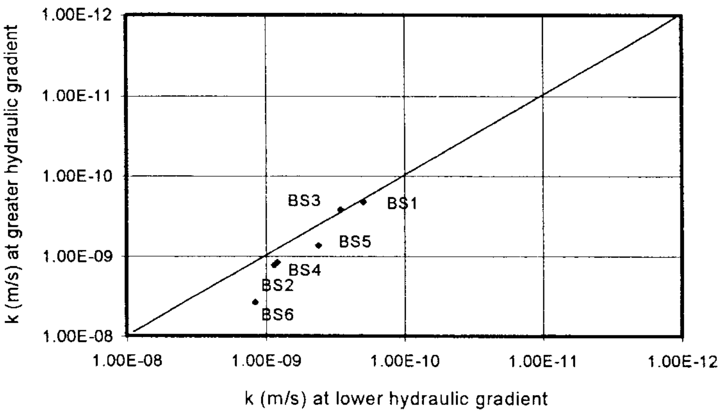

Fig.9 BS Permeability Values (m/s) for Changing Hydraulic Gradient from 30 to 125

In most of the tests carried out as part of the research there was no measurable influence due to change in hydraulic gradient within the range 10 to 125. This has been shown not to be the case for the drier MM specimens. At the end of the first stage of the BS tests the pressures were adjusted to examine the influence of increasing hydraulic gradient to that in the AP tests (i increased from 30 to 125). Though the average effective stress was maintained constant the increase in hydraulic gradient will have led to swelling at the inflow end of the specimen and further compression at the outflow. The results for Stage 2 shown on Fig.9 indicate that there was little influence on the wetter specimens MM(BS1) and MM(BS3) but the increase in hydraulic gradient resulted in an increase in permeability of up to 3 times for the drier more densely compact specimens.

CONCLUSIONS

(a) For the low plasticity MM material, depending on initial conditions, AP permeability results were often significantly greater (2 or 3 orders of magnitude greater) than the results for BS tests carried out with the same average effective stress.

(b) The stress paths followed in the BS and AP tests are significantly different, as are the end conditions. The AP specimens were saturated or near-saturated at the end of an AP tests but B values determined at the end of the test were often around 0.90.

(c) The average effective stress has a marked influence on permeability values. The hydraulic gradient also has an influence on the MM materials.

(d) Depending on initial conditions, swelling, elastic behaviour, yielding, irrecoverable plastic deformations, and collapse compression may be identified within the permeability tests.

(e) The Environment Agency accepts the BS test as an appropriate means of assessing the permeability of mineral liners and cappings for landfill sites. However, the sequential saturation, consolidation and permeability stages in a BS test are unlikely to be realised in practice. The potential variation in permeability results using different testing techniques is emphasised by the large variation in permeability recorded for the MM material using the BS and AP methods.

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