A NEW APPROACH FOR DETERMINING PERMEABILITY CHARACTERISTICS OF ROCK USING SLUG TESTING TECHNIQUES

T. R. C. Aston* and R. N. Singh**

* Cape Breton Coal Research Laboratory (CANMET), 210 George Street, Sydney, Nova Scotia, Canada.

** Department of Mining Engineering, University of Nottingham, University Park, Nottingham, NG7 2RD, United Kingdom.

ABSTRACT

A new technique of determining hydraulic flow characteristics of rock in the laboratory is presented. The technique is a laboratory simulation of a well known in situ 'slug' testing method where aquifer parameters are determined by the removal of water slug in a test borehole. The time taken for the water level in the borehole to return to its original rest level, is observed. The results are treated using an analytical technique, first developed by Theis [1]. The laboratory technique involves a test on a very small scale, with a slow rate of rise of water in a drill hole. The laboratory equipment and test procedure are described together with the advantages and limitations of the system. The technique offers an inexpensive, simple and effective method for determining the permeability of standard core samples, whilst keeping the amount of sample preparation to a minimum. The technique offers a potential for testing of most rock types under a variety of loading conditions.

INTRODUCTION

Permeability coefficient of rock is an important parameter, necessary in the studies concerned with groundwater hydrology, mine water inflow predictions and petroleum reservoir engineering. Various techniques have been used in the past for the determination of permeability characteristics of rocks, both in the laboratory and in rock mass. The laboratory techniques are useful for the determination of intra-granular permeability, directional permeabilities of anisotropic rock under a variety of stress conditions. It is also possible to measure the flow characteristics of a rock from intact state through fracture flow condition to a consolidated state in a single test. Two types of laboratory techniques are available : (a) direct technique for porous rocks [2] and (b) pulse technique for compact rock [3,4]. In this paper, an alternative approach based on in situ 'slug' testing method is described.

TEST PRINCIPLE

In essence, this technique can be used to determine rock permeability parameters by either the removal or injection of a water 'slug' in a small axial (blind) hole drilled on a cylindrical specimen and immersing the same in water. The time taken for the water level in the hole to reach to its original rest level is monitored.

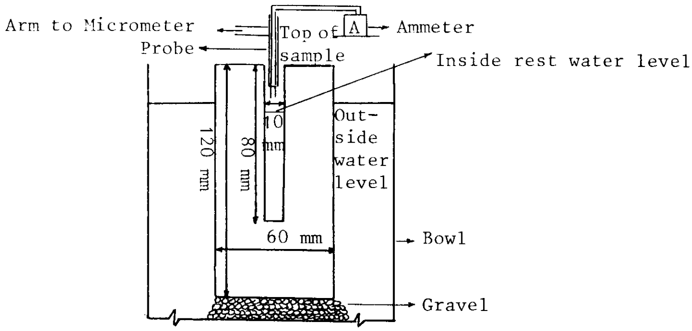

Figure 1. Apparatus for determining permeability by slug testing techniques

The equation for residual head in an instantaneous vertical line sink can be written, as equation (1). See Theis (1935).

$$S_h = \frac{Qe^{-\frac{r^2S}{4Tt}}}{4\pi Tt} \tag{1}$$

where S_h = Residual head after injection of a water slug (m)

r = Distance from the test well to an observation well (m)

t = Time since slug was injected measured from the average of the times marking the start and finish of the injection (min)

S = Storage coefficient (dimensionless)

T = Transmissivity (m^2/day)

Q = Volume of slug (m^3)

The success of test depends upon the similarity of the laboratory test conditions to that of an in situ test. If a small volume of water is added to a test well, the aquifer reaction to the injected slug is not normally measurable beyond the immediate well vicinity. Water level measurements are therefore only made in the injection well : the distance, r, then becomes the radius of the well, r_w. Since both r and r_w are small, and S is also small, the exponent of e in equation (1) approaches zero as it becomes large and the value of the exponential term approaches unity. If Q is expressed in m^3, T in m^2/day, t in minutes and S_h in metres, equation (1) can be re-written,

$$T = \frac{1440\ Q}{4\ S_h t} \tag{2}$$

or

$$T = \frac{114.6\ Q(1/t)}{S_h} \tag{3}$$

A plot of S_h against 1/t on arithmetic graph paper results in a straight line through the origin. T is calculated from the co-ordinates of any point on the straight line. However, in practice, actual well test data usually defines as exponential curve and a straight line can therefore only usually be drawn through the later data values. Early data is seldom plotted, which means that the scales can be expanded and a more accurate plot produced.

Apparatus and Test Procedure

The test apparatus shown in Figure 1, consists of a core sample 60 mm in diameter and 120 mm long into which has been drilled a 10 mm diameter axial hole to a depth of 80 mm.

Once a sample has been prepared, the drill hole is thoroughly washed with water, although acid can be used. The sample is then immersed in a larger container which is filled with water. A gravel base provides a complete hydraulic connection.

The sample is left for several days until water in the drill hole reaches a rest level. Once equilibrium is established, the hole can then be emptied using a pipette and the volume of water measured. Readings are then taken at regular intervals, to monitor the rise in water back to its original level. The resulting data is analysed using equation (3).

The water level is measured using two wire electrodes attached to a screw micrometer. The electrodes are lowered from a base reading, until contact is made with the water. An electrical circuit is then completed which registers as a deflection on a sensitive ammeter. Using this type of probe, the electrodes do not create artifically high water levels within the drill hole, due to capillary or surface tension effects.

Validity of the Technique

When well test data is analysed, certain assumptions are made concerning the conditions which exist within the aquifer medium and test well. These can be listed as seven main points, Kruseman and de Ridder [5] :

(1) the aquifer is apparently of infinite areal extent,

(2) the aquifer is homogeneous, isotropic and of uniform thickness,

(3) prior to pumping, the piezometric surface and/or phreatic surface are (nearly) horizontal,

(4) the discharge rate is constant,

(5) the aquifer is fully penetrated.

(4) The test hole and sample should be thoroughly clean, otherwise anomalous results might occur due to clogged pores.

(5) Water level in the bowl should remain constant, although significant evaporation losses can occur unless suitable precautionary measures are taken.

(6) Composition of the water, can result in permeability changes due to chemical, physical or bacteriological action on the sample. Ideally, distilled water should be used during experiments although this seldom resembles the water encountered under field conditions.

Analysis of Test Results

Tables 1 and 2 show test data collected from two samples of Darley Dale sandstone. Sample A is a normal specimen, while Sample F has been subjected to intact failure under uniaxial compression. Table 3 shows recovery levels for the two samples, A and F, and Figure 2 a graph of Residual Head (S_h) against the Reciprocal of Time (1/t) for both specimens.

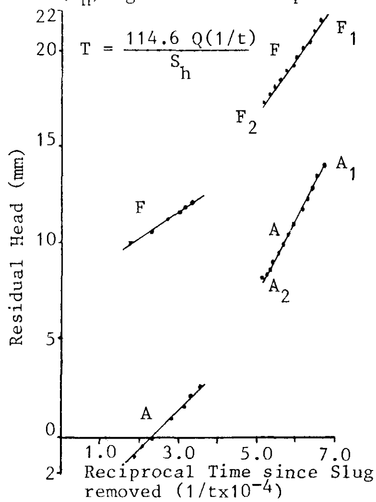

Figure 2. Residual Head (S_h) against the Reciprocal of Time (1/t) for Samples A and F

Values taken from Figure 2 for substitution in equation (3) are :

Sample	S_h	1/t
A_1	1.41×10^{-2}	6.75×10^{-4}
A_2	0.92×10^{-2}	5.50×10^{-4}
F_1	2.16×10^{-2}	6.75×10^{-4}
F_2	1.70×10^{-2}	5.25×10^{-4}

In addition, for unsteady methods only,

(6) storage in the well can be neglected,

(7) water removed from storage is discharged instantaneously with decline in head.

Although aquifers of infinite lateral extent do not exist, many are so wide that for all practical purposes they can be considered to be. The assumption that aquifers are isotropic and homogeneous is probably never met in practice. All aquifers contain lithological variations which effect the permeability. Similarly, the necessity for aquifers to be of constant thickness is not necessary, since the development of a cone of depression will seldom vary much with aquifer thickness. Therefore, in many actual situations, no serious errors result if not all the assumptions are fulfilled.

The laboratory testing procedure is considered to fulfil many of the theoretical criteria mentioned by Kruseman and de Ridder [5].

Advantages of the Technique

(1) If a test sample is chosen carefully, its small size will correspond more readily to an isotropic and homogeneous medium.

(2) The bowl of water in which the sample rests can be assumed to be of infinite areal extent, since the volume of water removed during testing is very small when compared with the total volume in the system.

(3) The drill hole diameter is small compared to the sample diameter.

(4) A cone of depression develops within the sample which is equivalent to that developed around large scale test wells.

(5) Radial flow and hence Darcian conditions should be developed around the drill hole.

(6) The laboratory technique resembles more closely the theoretical assumptions for deriving aquifer parameters, than the actual field techniques.

Disadvantages of the Technique

(1) The technique involves working on a very small scale, with water volumes of several cm^3 and a rate of rise in the drill hole of mm/hour.

(2) Technical difficulties are posed by measuring the very small changes in water level which occur in the narrow diameter drill hole. The probe must be sufficiently small so as not to create artifically high water levels due to capillary effects.

(3) The test assumes the sample and water to constitute a single isotropic, homogeneous aquifer medium, whereas in reality a boundary condition may exist.

Table 1 - Test Data for Darley Dale Sandstone, Sample A

	22/6 (9.36 am)	24/6 (10.03 am)	26/6 (11.50 am)
Top of Sample	81.79	81.91	82.0
Outside Water Level	55.62	56.13	55.88
Inside Rest Water Level	56.26	-	-

Actual Volume of Water Removed - 4.56 cm^3

Theoretical Volume of Water Removed - 4.59 cm^3

Time since start of Recovery (mins)	Micrometer Reading (mm)	Amount of Recovery (mm)
0	23.24	0.00
30	24.23	0.99
59	25.96	2.71
94	27.68	4.44
121	28.72	5.48
150	29.87	6.63
191	31.60	8.35
210	32.39	9.14
246	33.78	10.54
286	35.41	12.61
344	37.39	14.14
405	39.57	16.33
1505	65.66	42.42
1534	66.37	43.13
1569	66.98	43.74
1630	67.43	44.20
1650	68.29	44.96
1677	68.60	45.36
1709	68.98	45.74
1737	69.29	46.05
1776	69.64	46.40
1801	70.00	46.76
1837	70.51	47.27
1876	70.56	47.32
2907	77.14	53.90
2998	77.39	54.15
3147	77.90	54.66
3442	78.36	55.11
4265	79.63	56.39
5894	80.69	57.45

Table 2 - Test data of Darley Dale Sandstone, Sample F

	22/6 (9.21 am)	24/6 (9.55 am)	26/6 (11.51 am)
Top of Sample	84.07	84.33	84.33
Outside Water Level	56.21	55.88	56.08
Inside Rest Water Level	59.46	-	-
Actual Volume of Water Removed	4.10 cm^3		
Theoretical Volume of Water Removed - 4.15 cm^3			

Time since start of Recovery (mins)	Micrometer Reading (mm)	Amount of Recovery (mm)
0	6.63	0.00
24	6.73	0.10
39	7.19	0.56
56	7.56	0.94
69	8.13	1.50
113	9.73	3.10
132	10.62	3.98
169	11.86	5.23
204	13.10	6.47
230	14.35	7.72
259	15.36	8.73
306	17.02	10.39
353	18.67	12.04
439	20.95	14.32
1514	44.78	38.15
1552	45.31	38.68
1581	45.69	39.06
1621	46.25	39.62
1662	46.71	40.08
1695	46.94	40.31
1721	47.29	40.66
1756	47.50	40.87
1787	47.83	41.20
1819	48.08	41.45
1850	48.41	41.78
1894	48.64	42.01
2914	54.00	47.34
3015	54.05	47.42
3159	54.25	47.62
3461	54.63	48.00
4279	55.50	48.87
5910	56.21	49.58

Table 3 - Time and Recovery Levels within the Normal and Stressed Samples

Sample A (Normal)			Sample F (Stressed)		
t	1/t	S_h	t	1/t	S_h
(mins)	$\times 10^{-4}$	(mm)	(mins)	$\times 10^{-4}$	(mm)
0	-	56.26	0	-	59.46
30	333.0	55.27	24	417.0	59.36
59	169.0	53.54	39	256.0	58.90
94	106.0	51.82	56	179.0	58.52
121	82.6	50.77	69	145.0	57.96
150	66.7	49.63	113	88.5	56.36
191	52.3	47.90	132	75.8	55.47
210	47.6	47.11	169	59.2	54.23
246	40.7	45.72	204	49.0	52.98
286	35.0	44.09	230	43.5	51.74
344	29.1	42.11	259	38.6	50.72
405	24.7	39.93	306	32.7	49.07
1505	6.64	13.84	353	28.3	47.42
1534	6.52	13.13	439	22.8	45.13
1569	6.37	12.52	1514	6.61	21.31
1603	6.24	12.06	1552	6.44	20.77
1650	6.06	11.30	1581	6.33	20.39
1677	5.96	10.89	1621	6.17	19.83
1709	5.85	10.51	1662	6.02	19.38
1737	5.76	10.21	1695	5.90	19.15
1776	5.63	9.85	1721	5.81	18.80
1801	5.55	9.50	1756	5.69	18.59
1837	5.44	9.00	1787	5.60	18.26
1876	5.33	8.94	1819	5.50	18.00
2907	3.44	2.36	1850	5.41	17.67
2998	3.33	2.11	1894	5.28	17.45
3147	3.18	1.60	2914	3.43	12.11
3442	2.91	1.14	3015	3.32	12.04
4265	2.34	-0.13	3159	3.17	11.83
5894	1.70	-1.19	3461	2.89	11.45
-	-	-	4279	2.34	10.59
-	-	-	5910	1.69	9.88

where the volume of water removed is

Specimen A = 4.56 cm^3 = 4.56×10^{-6} m^3

Specimen F = 4.10 cm^3 = 4.10×10^{-6} m^3

Therefore using $T = \frac{114.6\ Q\ (1/t)}{S_h}$ (3)

Table 4

Calculated Results

Sample	Transmissivity (T)	Permeability (k)
A_1	2.50×10^{-5}	3.12×10^{-4}
A_2	3.12×10^{-5}	3.90×10^{-4}
F_1	1.47×10^{-5}	1.84×10^{-4}
F_2	1.45×10^{-5}	1.81×10^{-4}

where k is calculated using the following equation

$$T = kD \tag{4}$$

where T - Transmissivity

k - Permeability

D - Aquifer Thickness

D in this case is taken as the penetration depth of the drill hole - 8.0×10^{-2} m.

The results show that a decrease in permeability has occurred within the stressed sample. This can be associated with crushing of the pore spaces and a reduction in intergranular permeability. A significant change from micro to macro fissuring within the stressed sample does not appear to have occurred and is probably due to the intact nature of the specimen after failure.

DISCUSSIONS AND CONCLUSIONS

The technique offers economic, simple and effective method for determining the permeability of standard core samples, while keeping the amount of sample preparation to a minimum. Using standard uniaxial testing procedures, it is possible to determine whether a relationship exists between permeability and the induced strain on a specimen. Similarly, with the advent of Stiff Testing Machines it should be possible to monitor the post-failure permeability characteristics of a sample.

Using a series of control samples, it should be possible to vary the drill hole characteristics in order to simulate different well types and aquifer conditions. A hole drilled completely through the sample could be sealed at one end using resin or glue and used to simulate a fully penetrating well system. Similarly, the effect of variations in hydrochemistry and bacterial growth on or within a specimen could also be assessed. If large scale triaxial cells were available, the technique could also be extended to monitor the permeability changes associated with loading under triaxial conditions.

Finally, the technique offers almost unlimited potential for the testing of most rock types under a variety of loading conditions. However, rock types which disintegrate when in contact with water, such as mudstones, could not be used. The method could therefore prove useful for solving many of the hydrogeological problems encountered in both coal and metalliferous mining.

ACKNOWLEDGEMENTS

The authors acknowledge the help given by Mr. V. Cassapi, experimental officer, Nottingham University for the design of the laboratory test equipment. Thanks are also due to Mr. J. Black, Severn-Trent Water Authority, Malvern for many useful discussions. The work outlined herein forms part of a wider Rock Mechanics research programme and as such acknowledgement must be made of Prof. T. Atkinson and Dr. B. N. Whittaker, Rock Mechanics research co-ordinators.

REFERENCES

1. Theis, C. V., The relationship between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground water storage, Transactions, American Geophysical Union, p.519-524, (1935).

2. Kanu, A. B. S., 'A study of the flow of water through rock fractured under triaxial compression', M.Phil Thesis, University of Nottingham (1978).

3. Yamada, S. E., 'A review of pulse technique for permeability measurements', Society of Petroleum Engineers Journal, Vol.20, Part 5, pp.357-58, (1980).

4. Brace, W. F. et al., 'Permeability of granite under high pressures', Journal of Geophysical Research, Vol.73, No.6, March 15 (1968).

5. Kruseman, G. P. and De Ridder, N. A., 'Analysis and evaluation of pumping test data', published by International Institute for Land Reclamation and Improvement/ILRI, P.O. Box 45, 6700 AA Wageningen, The Netherlands, 1979.