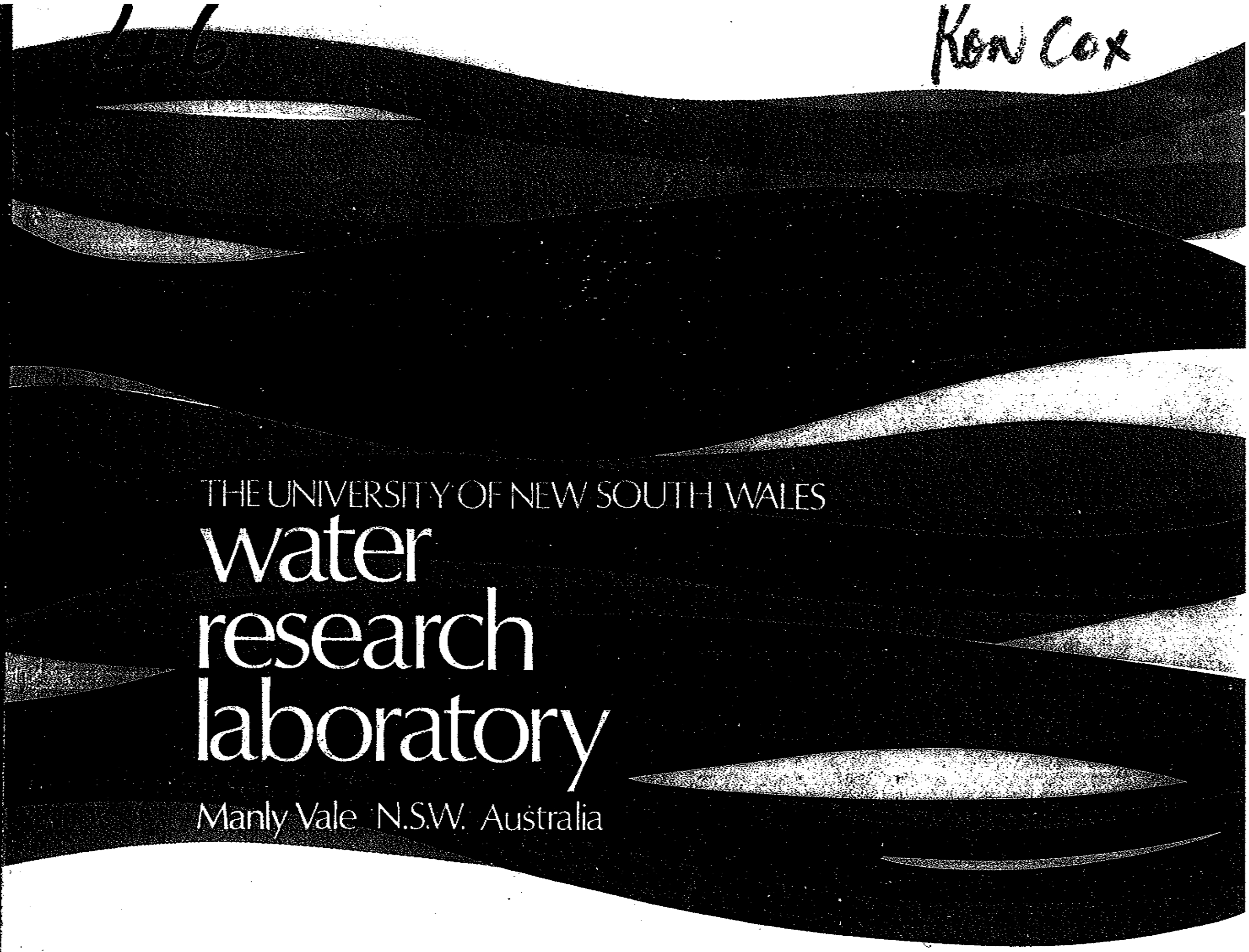
Ken Cox



THE UNIVERSITY OF NEW SOUTH WALES

water research laboratory

Manly Vale N.S.W. Australia

DRILLING MUD INVASION OF UNCONSOLIDATED AQUIFER MATERIALS

by

C.R.DUDGEON and R.J.COX

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PART III

Preface

This report covers work carried out for the Australian Water Resources Council on Research Project 71/25 "Drilling and Development Problems in Unconsolidated Sediments." The study involved numerical analysis of the effects of permeability reduction and improvement caused by drilling and development in water well construction and an experimental study of drilling mud invasion of aquifer materials.

The studies were carried out at the Water Research Laboratory of the University of New South Wales under the supervision of the project leader, Mr. C.R. Dudgeon. Dr. P.S. Huyakorn was responsible for the numerical study reported in Part II while the experiments with drilling mud described in Part III were the responsibility of Mr. R.J. Cox.

The assistance of other members of the staff of the Water Research Laboratory is gratefully acknowledged, particularly that of Mr. W.H.C. Swan who worked on the project in its early stages. The authors also wish to express their gratitude to members of the project reference panel for practical guidance during the course of the project.

PART III

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1. Introduction

The majority of water wells in Australia are drilled by either cable tool or mud rotary methods. Each method has its advantages and disadvantages, and both should be considered for any drilling operation. Detailed descriptions and relative merits of the various drilling techniques are well documented (in particular Gatlin, 1960; Stanley, 1973; and Johnson, 1966).

All drilling methods impair the ability of an aquifer to deliver water to a drilled hole. This impairment may be due to physical rearrangement of the matrix of the aquifer material. However, formation damage caused by the invasion of foreign fluids and/or solids into the exposed aquifer is well recognised as the main cause of reduced permeability around the hole.

Any form of rotary drilling relies on excess hydrostatic head to maintain an open hole. This pressure differential will naturally force both drilling fluid and cuttings against the walls of the hole. If the aquifer pores are large enough, then particles will be accepted by the aquifer. This is particularly relevant where drilling mud is used. The mud itself is composed of fine clay and/or polymer material which can be forced a considerable distance into the aquifer despite the wall cake building properties of the muds.

Cable tool drilling churns the cuttings into a thick slurry and the surging action of the tools can force slurry into the aquifer. There is a trend towards increased usage of drilling muds with cable tool plants. Mud additives can keep the casing free in swelling sections and their use is essential in controlled artesian well completions. It is common practice in New South Wales to construct holes larger than 12 inch diameter with drilling mud to keep the hole open (no casing), using the cable tool method (Johnstone, 1974).

The drilling mud, originally regarded only as a medium for lifting the cuttings to the surface in rotary drilling, is now recognised as a major factor in the successful completion of many drilling operations.

The deeper the drilling operation the more expensive and important is the maintenance of a suitable mud system. Drilling mud technology is quite sophisticated largely due to the demanding requirements for drilling muds suitable for successful completion of oil wells under a wide range of conditions. Much time and money has been spent by the oil industry in examining many aspects of drilling mud control. The text by Rogers (1963) is a detailed volume covering all facets of drilling mud technology. An abundance of literature is also available through technical papers distributed by the major mud supply companies.

Although both the oil and water well industries have individual problems peculiar to themselves, there is an area of common interest pertaining to the drilling, completion and development of efficient production wells. It is the author's opinion that more use of the published material from the oil industry should be made in groundwater applications. A large volume of research has been published by the oil well industry on the closely related subjects of formation damage and lost circulation. Both Rogers (1963) and Gatlin (1960) review the major contributions in this important field. No detailed resume will be attempted here although references to publications of particular interest are included in the bibliography. In broad terms the relevant aspects of formation damage covered by this literature will now be summarised.

(a) The mechanisms of formation and erosion, ease of removal, and fluid loss control exhibited by the mud filter cake which builds up at the walls of the hole have been studied for a wide range of muds and drilling conditions.

(b) There has been considerable evidence of the formation of internal filter cake layers initiated by bridging of invasion solids within the pores of the aquifer material.

(c) Substantial solid particle invasion is possible prior to the formation of an effective stable wall and/or internal cake.

(d) The loss of the fluid component (filtrate) of the mud to the aquifer may continue even after the stable wall and/or internal cake layers have formed. The continuing steady rate of loss of mud filtrate will depend upon the permeability of the developed cake layers. The depths of invasion of mud filtrate will thus be considerably greater than those of the solids. In oil well applications filtrate invasion may be highly detrimental to the aquifer. In water well applications filtrate invasion will generally not be a problem if a water base mud is used (normally the case).

(e) Permanent reductions in the permeability of aquifer materials have been found in many instances even after only minor exposure to various drilling muds. This considerable formation damage could not be removed even by extensive development.

Despite the literature from the oil industry, there are many unanswered questions pertaining to the extent of possible formation damage when drilling the aquifers commonly tapped for water supplies. These uncertainties arise because of major differences in application between the oil and water well fields which may be briefly summarised as:-

(a) The aquifer materials considered good for water production are far more permeable than those considered to be economically viable in the oil industry.

(b) Drilling muds used in water well applications are usually low solids - low weight water base muds which are a long way from the complex, mud systems commonly employed in oil well drilling.

(c) Bottom hole pressures and temperatures are low in drilling a water well when compared to the extreme values commonly encountered in oil well drilling.

(d) The time to drill a water well is relatively short and as such the aquifer is exposed to possible formation damage by the drilling mud for only a limited period.

A more particular experimental investigation of the problem of formation damage (and the related problem of lost circulation) as relevant to the water well field was carried out during the course of this project. A series of experiments was made in which a range of unconsolidated aquifer materials were exposed to commonly used water well drilling muds under various flow conditions. Details of these experiments are set out in the following sections.

2. Experimental Testing

2.1 General

The need for experimental investigation of possible formation damage to unconsolidated aquifer materials by exposure to drilling muds under various flow conditions was discussed in Chapter 1.

A description of the experimental mud circulation rig and its operation is given in this chapter. Details of testing procedures, aquifer materials and mud systems tested, and further measurement techniques are also included. Further background material is presented where relevant.

2.2 Test Equipment

A schematic flow diagram of the experimental mud circulation rig is shown in Figure 1.

The system shown was designed to circulate drilling mud parallel to the faces of aquifer material samples mounted in separate detachable sample containers. Four samples could be mounted in the test apparatus cell at any one time.

The 20 H.P. Warman 3/2 split casing slurry pump used was capable of delivering 100 gpm against a head of 110 feet.

The test apparatus cell to which the individual aquifer samples were attached consist of a 195 mm I.D. P.V.C. pipe with an internal centrally positioned 150 mm O.D. cylinder. The flow of mud through the test cell took place in the annular space and simulated the dynamic

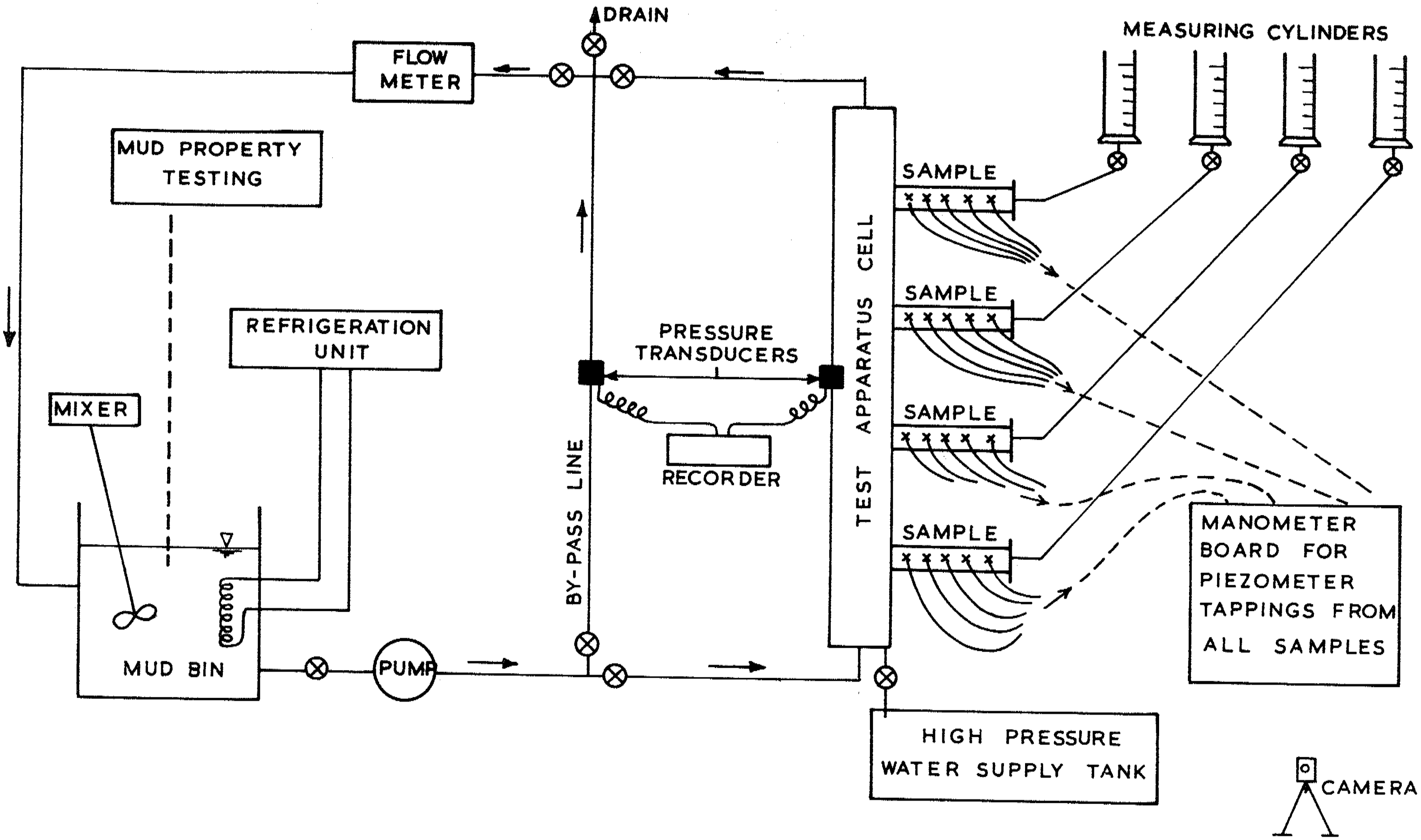


FIGURE 1: FLOW DIAGRAM OF EXPERIMENTAL MUD CIRCULATION RIG

flow conditions that exist up the hole above the bit during rotary drilling.

The material samples were mounted in a vertical position beneath the test cell in such a manner that the exposed material surfaces were flush with the outer 195 mm diameter of the annular mud flow area. Each material sample container could be easily attached and detached from the test apparatus cell by a simple fitting involving an 'O' ring seal and five bolts equispaced around a flange. Details of the sample containers and their coupling to the test cell are shown in Figure 2. Each container was made from clear 90 mm I.D. acrylic pipe and when loaded contained a material sample 450 mm in length. The aquifer material was constrained by a suitable filter cloth mounted at the base of the sample as shown. Five piezometer tappings at the spacing shown were set into the wall in a line along the length of the container. Each tapping was connected to a mercury water manometer for measurement of the piezometric head within the aquifer sample. The five tappings enabled reasonably reliable measurement of permeability variations within the sample to be made at any time.

Mud fluid which was discharged through the aquifer material samples was collected in easily read measuring cylinders. Flexible plastic tubing (25 mm diameter) was used to carry the passed fluid from the base of the samples to the measuring cylinders. Flow from a particular sample could be controlled by a valve below the relevant measuring cylinder.

Under non-circulation conditions, the test apparatus cell could be isolated and pressurised up to a value of 25 metres of water head by connection to a high pressure constant head supply.

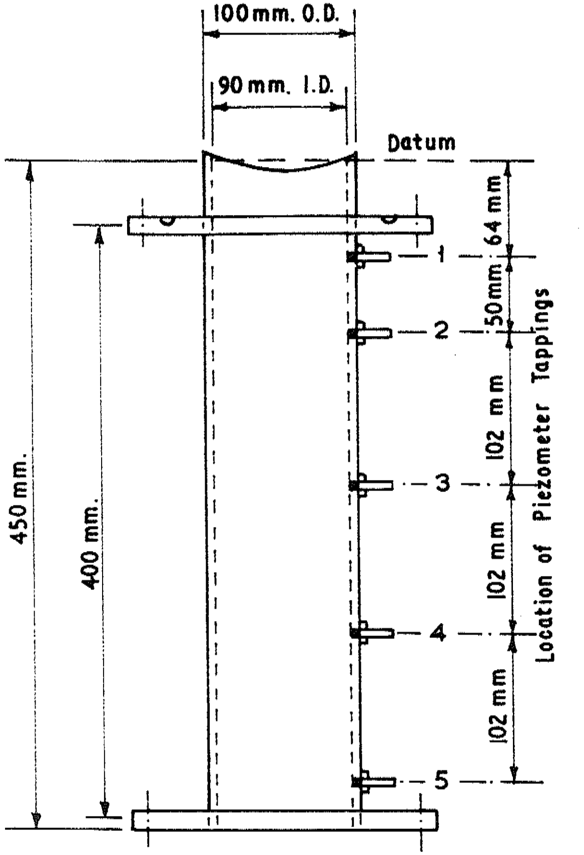
Mud was mixed and stored in the mud bin shown. To aid in mud mixing and preparation the pump was used to circulate the mud through the by-pass line.

The temperature of the mud was maintained at approximately an atmospheric value by the coupling of a large refrigeration unit to a series of copper cooling coils set within the mud bin.

Both mud flow velocities and pressures were controlled by suitable throttling of the valves within the system.

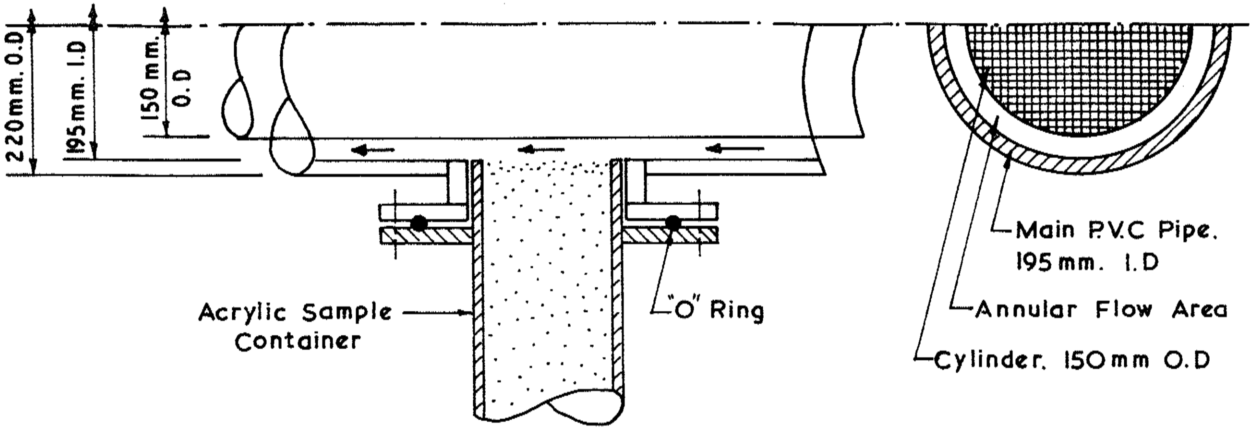
Mud flow velocities were measured by means of a calibrated elbow bend meter or an orifice in the base of a tank.

Pressure transducers were used to give a continuous recording of mud flow pressure fluctuations in both the by-pass line and the test apparatus cell.

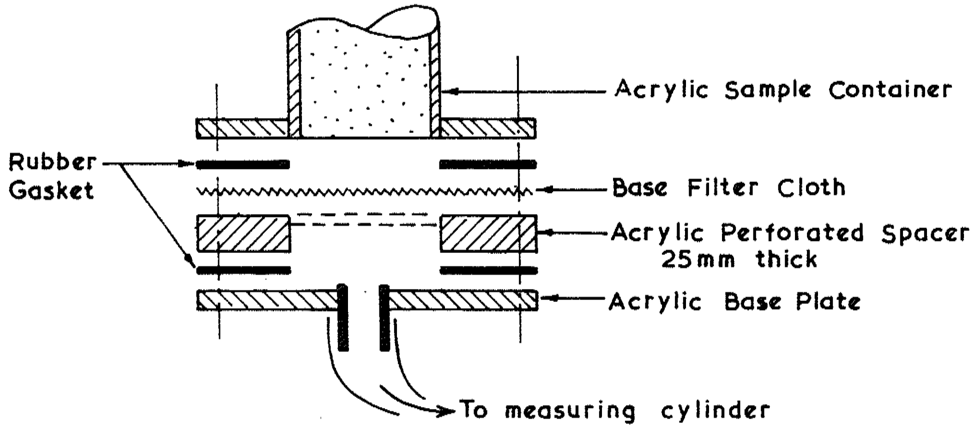


ACRYLIC PIPE & FLANGES
SAMPLE CONTAINER

Note: All acrylic flanges are
15mm thick unless specified



CONNECTION DETAIL
SAMPLE CONTAINER - MAIN P.V.C TEST CELL



SAMPLE CONTAINER - BASE DETAIL
(exploded view)

FIGURE 2: SAMPLE CONTAINER DETAILS

2.3 Test Procedure

The four different aquifer materials for exposure to the mud flow were equally compacted in 50 mm layers when the sample containers were filled. The porosity of each material was calculated from the measured weight of material required to fill the container. Each container was mounted in the test apparatus cell which had been isolated from the rest of the mud circulation system. The base discharge end of each sample was connected through water filled plastic tubing to the valve at the upstream side of the respective measuring cylinder.

The test cell was connected to the high pressure constant water supply tank and enough pressure applied to induce a flow of water through each sample. After several hours of pressurised water flow, all air had been removed from the sample materials. The piezometer tappings in the walls of the now fully saturated samples were connected to their respective manometers. Permeability testing of the individual material samples was carried out by measuring the piezometric head variations along the sample for several monitored velocities of flow through the material (see Section 2.5 for specific details).

The water within the test cell was drained until level with the surfaces of the sample materials. This level was used as the reference datum line for all recorded pressure heads. The sample materials were thus in a fully saturated condition at the start of the test. All valves between the base of the samples and the measuring cylinders were fully open. The measuring cylinders were so arranged that an initial reading of zero was recorded at this stage. Prior to the start of a test, 1 cubic metre of the desired mud was prepared by mixing in the mud bin and/or circulating through the by-pass line at the test flow rate and pressure. The flow rate and pressure were controlled by suitable throttling of the valves in the system. During this time the refrigeration unit controls were adjusted to maintain a constant mud temperature at approximately the atmospheric value. Testing of the mud properties (as described in detail in Section 2.6) was carried out at regular intervals during pre-test circulation to ensure that the test would not be commenced until the properties of the mud were reasonably constant.

After satisfactory ageing of the mud system, the drilling mud was introduced to the test cell. The mud flow velocity and pressure in the test cell were quickly adjusted to the desired values within the initial stages of the test. Usually this adjustment was completed within 15 seconds. In some tests, however, fluctuations occurred over the duration of testing. In all tests the target value of mud velocity past the face of the sample materials was 120 ft/min. which is a generally accepted value consistent with efficient removal of cuttings when rotary drilling with mud. For the majority of water wells drilled in Australia, the downhole pressure differential between the mud and the aquifer will never exceed 25 psi. Test target values for mud pressure above the sample aquifer materials were either 10 psi or 20 psi.

For the duration of the test, readings were taken of cumulative fluid discharged from each material sample. This enabled an estimate of filtration rates and possible filter cake development with time of exposure.

Regular mud property testing (as described in Section 2.6) was carried out during the period of testing.

The piezometric head variations within each material were obtained at specific times after the start of mud flow from photographs taken of the manometer boards to which all sample tappings were connected. Generally photographs were taken at times of $\frac{1}{2}$, 1, 2, 5, 10, 20, 40 and 60 minutes. The time variation of piezometric head distribution with a particular sample clearly defined changes in permeability within the material. The position of filter cakes and/or internal cake seals with very low permeabilities were quite easily pinpointed from this piezometric head data.

After a certain period of mud circulation the flow through the test cell was stopped. In some tests the mud was immediately washed from the test apparatus whilst in others static mud exposure conditions under various pressures were continued for different times.

Eventually all mud was drained from the test cell which was then gently washed clean of all mud. In some instances the samples were then removed and visually inspected before being remounted on the test cell.

Most samples tested suffered some degree of formation damage. Further permeability testing of the material samples after varying degrees of attempted sample rehabilitation was carried out. In this manner subjective evaluation of the possible effectiveness of different methods of development was obtained. By comparison with the original unexposed material flow behaviour, estimates of possible permanent formation damage were made.

Full details of each test are given in Appendix V.

2.4 Unconsolidated Aquifer Test Materials

The grain size distributions of the aquifer materials used in the various mud exposure tests are shown in Figure 3. Generally the sample materials were specifically made up to meet the required grading. The make up material was drawn from both Nepean River sands and gravels and Cronulla beach sands.

Useful measures of the distribution of particles within the material are the effective diameter and the uniformity coefficient. The effective diameter will be defined as the diameter that 10 per cent of the material is finer than, D_{10}. The effective diameter can (with reservations) be used as a guide to relative permeability differences between similar materials. The uniformity coefficient defined as the ratio of the D_{60} to D_{10} sizes is an index of the variation of particle size grading within the material.

The important constants for each of the materials shown in Figure 3 may be briefly tabulated.

Material Number	Effective Diameter D_{10}(mm)	Uniformity Coefficient D_{60}/D_{10}
1	0.22	1.3
2	0.5	1.4
3	1.3	1.3
4	3.0	1.3
5	0.24	3.7
6	0.5	7.2
3/16" Pea Gravel	1.5	2.6

2.5 Permeability Testing of Material Samples

Controlled pressures could be applied to the isolated test cell apparatus by suitable adjustment of the valve between the test cell and the high pressure water supply tank. This applied pressure could be used to induce water flow through any one of the loaded material samples. By simultaneously recording both the piezometric head distribution across the sample length and the flow rate through the sample, the sample container could be effectively used as a permeameter.

During mud circulation testing, pressure drops up to 20 psi were to be applied across the sample materials. It was considered logical to carry out permeameter testing of the aquifer materials at comparable values of hydraulic gradient. From past experience, it was recognised that many of the aquifer test materials would not obey Darcy's

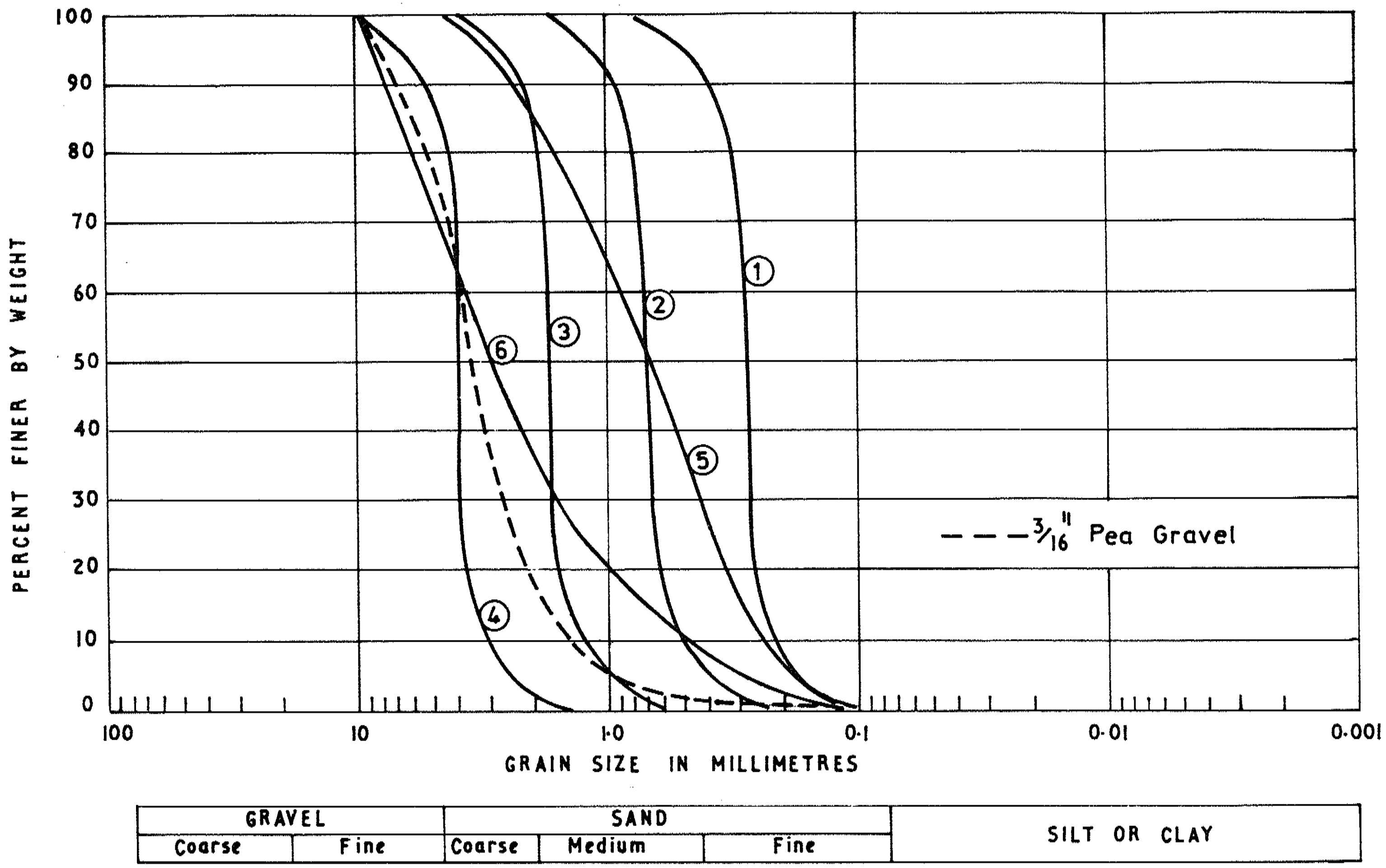


FIGURE 3: GRAIN SIZE DISTRIBUTION FOR VARIOUS TEST MATERIALS

law at such high gradients. To obtain a reasonable definition of the degree of non-linear flow, permeameter testing of each material was carried out over a range of applied pressures.

Only one material sample was tested at a time:

Pressure was applied gradually to the test cell until a flow from the sample was induced. The pressure was then steadily increased to a maximum value of 25 psi with the valve downstream from the sample in a fully open position. Water was run through the sample at this maximum possible flow rate for approximately 15 minutes. This procedure was employed to wash out very fine material from the sample and to allow any possible settlement of the sample to occur prior to further testing.

Both the piezometric head distribution across the sample and the flow discharge from the sample were recorded for a range of decreasing pressures applied to the test cell and measured by pressure transducer. The velocity of flow through the sample was simply calculated from the discharge rate obtained by volumetric measurement. Any inhomogeneity in the sample was shown up in the distribution of piezometric head recorded by the manometers to which the wall tappings were connected. The head at the sample face was calculated from the reading given by the pressure transducer in the top of the test cell.

Generally results were obtained for three flow velocities.

If the material exhibited non-linear flow behaviour then the Forchheimer equation relating hydraulic gradient (i) and velocity (V) was assumed to be applicable i.e.

$$i = aV + bV^2 \qquad (1)$$

where a and b are referred to as the non-linear Forchheimer equation coefficients.

The i-V relationship for each material was presented on a log-log plot in the form i/V versus V. In this form materials obeying Darcy's law are readily recognised since they plot as a horizontal line. A curve away from the horizontal clearly indicates deviation from Darcy's law by materials exhibiting non-linear flow behaviour. The dimensionless parameter b/a^2 was used as a measure of the degree of non-linearity exhibited by a particular material.

For materials which resulted in values of $b/a^2 > 0.1$ insufficient testing was carried out at the lower velocities to give any reliable estimate of a coefficient of hydraulic conductivity (K) where K is given by Darcy's law

$$V = Ki \qquad (2)$$

(Note: At low flow velocities the bV^2 term of the Forchheimer expression becomes negligible and the Forchheimer equation becomes Darcy's law with $K = 1/a$).

The term "permeability" will be loosely used in this section of the report to generally describe the flow behaviour of a porous medium.

2.6 Mud Property Testing

All testing of muds was carried out in accordance with A.P.I. standard procedures. Detailed descriptions of such tests may be found in Rogers (1963), Gatlin (1960), A.P.I. specifications or in many of the suppliers' reference manuals.

A number of simple field tests can be conducted to determine basic mud properties:-

Temperature.

Density or Mud Weight: A beam balance is the A.P.I. recommended instrument. The density of a known volume of mud can be measured in pounds per U.S. gallon; pounds per cubic foot; pressure per hundred feet of head or as specific gravity.

Viscosity: 1500 cc of fresh mud is placed in a Marsh Funnel and A.P.I. specifications call for the timing of the flow of one U.S. quart out of the funnel. Viscosity of water is 26 seconds Marsh Funnel whilst muds for drilling of water wells range from 30 to 50 seconds.

Filtrate Loss: A sample of mud is placed in a filter press and subjected to a pressure of 100 psi. The bottom of the press cell is closed by a Whatman No. 50 filter paper. The cumulative volume of filtrate passed through the filter paper should be recorded in cc at times of both 7½ and 30 minutes. More will be said of the interpretation of this test later.

Wall Cake: At the conclusion of the filtrate loss test, the filter cake set on the filter paper is washed free of excess mud and the thickness and nature of the residue cake recorded.

Sand Content: A known quantity of mud is taken, diluted with water and passed over a 200 mesh sieve. After washing, the sand is measured and reported in per cent by volume.

At present very little field testing of muds is carried out in Australia. It is recommended that the above listed series of simple field tests be carried out at least once per day as a particular step in encouraging drillers to exercise more mud control. The results of such simple tests may also prove useful to the drilling engineer in estimating possible formation damage.

More detailed chemical analyses of the mud filtrate may be necessary in some difficult areas to aid in selection of appropriate mud additives to enable hole completion. In such instances either the geologist or the drilling engineer or suitably qualified personnel should be on site to carry out such testing.

Many low solids mud systems show a considerable initial spurt when carrying out standard filtrate loss testing as described above. A typical time history of filtration loss during such a 30 minute test for such a mud is shown in Figure 4.

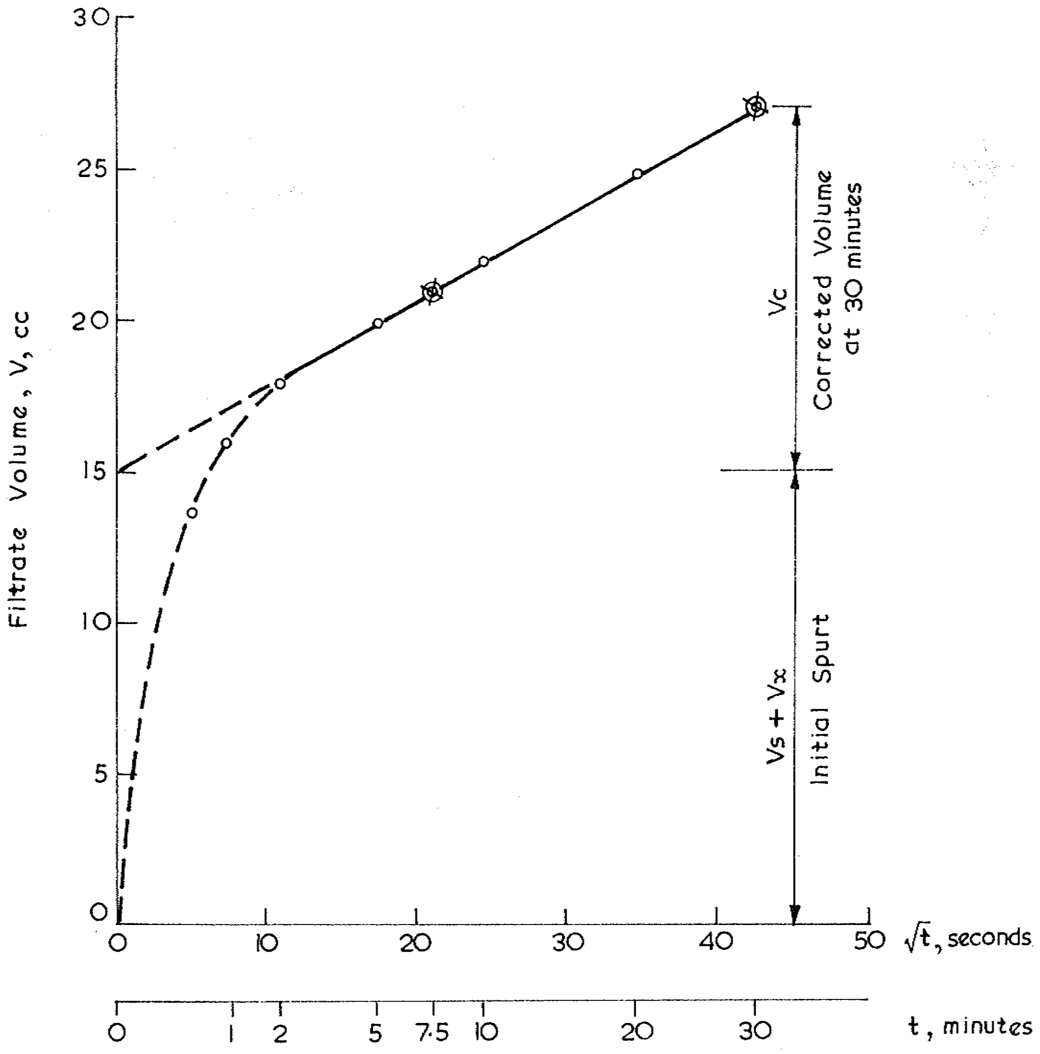


FIGURE 4: FILTRATE LOSS - STANDARD API METHOD

For such a mud it is important to obtain both the corrected 30 minute water loss (corrected volume = V_c) and the initial spurt or surge correction ($V_s + V_x$). The corrected volume is the basic measurement and is widely used for mud control purposes. Beeson and Wright (1950) suggested that the generally disregarded intial spurt was indicative of the invasion of the aquifer which occurs prior to the formation of either wall cakes and/or internal filter cakes. Thus the necessity for recording the $7\frac{1}{2}$ and 30 minute filtrate volumes.

The Marsh funnel viscosity in seconds is a useful comparative measure of viscosity for field drilling mud control. However, drilling muds exhibit non-Newtonian plastic and thixotropic viscosity characteristics. As such the viscosity of the mud varies with previous history and the rate of shear at which it is measured. Multispeed viscosimeters are available for A.P.I. specification testing. In water well applications more specific viscosity testing would in general only be carried out for laboratory pilot testing of mud systems to determine the possible effects of various additives and contaminants and new mud products. Experienced personnel should carry out such testing if any reliability is to be attached to the resulting values of apparent viscosity (centipoises, cps), plastic viscosity (cps), yield point (lb/100 sq.ft.) and gel strength (lb/100 sq.ft.).

The importance of these measures of the rheological properties of a drilling mud is discussed in detail by Rogers (1963) and a brief discussion only will be given.

Abnormally high viscosity may be caused by increases in either plastic viscosity or yield point. For practical purposes, plastic viscosity depends upon the concentration, size and shape of mud solids. The control of solids is thus very important in controlling viscosity. High plastic viscosity reflects increased friction due to the introduction of solids into the system and/or grinding of the particles to a smaller size. Yield point is a measure of the electro-chemical attractive forces in a mud under flow conditions. The yield point component of viscosity may be controlled by proper chemical treatment. Gel strengths are a measure of the attractive forces under static or non-flow conditions and should not be confused with yield point. Gel strength values denote the thixotropic properties of the mud. Generally gel strengths will decrease as the yield point decreases. Gel strength in a mud is important and should be controlled at the lowest practical value. Progressive or strong gels should be avoided. A progressive gel is one that may start low initially, but consistently increases with time.

2.7 Mud Systems

2.7.1 General

The most commonly used mud system for water well drilling consists of fresh water with bentonite clay plus further selected additives. Straight bentonite clay drilling muds can require considerable time to hydrate fully. In water well applications where hole completion times are low, such a waiting time often proves unacceptable.

The commercially available high yield clay base muds offer many advantages over a straight bentonite system. These products, essentially prepared mixtures of bentonite plus selected additives (mostly polymer) are widely used in the water well industry. Generally, overall lower drilling times can be achieved due to advantages in logistics, handling, lower hydration times and easier mud control and maintenance, all of which in themselves are very important to the driller. Mud costs will also usually be lower using a high yield product.

Recent innovations include the use of long chain polymers and bio-degradable additives to build low solids muds. These products will build viscosity in both fresh and salt waters, prevent hydration of clays and give controlled filtration properties to the mud. The major claimed advantage of these muds is that they can be broken back to the viscosity of water by the addition (or lack) of a further additive to ensure the removal of any filter cake or plugging of the aquifer that occurs during drilling. More will be said later regarding these claims for the minimisation of formation damage in the light of results from the tests conducted in this project.

The Water Conservation and Irrigation Commission of New South Wales conducted a comparative series of field drilling tests in 1970 with two of the bio-degradable muds available in Australia. A favourable report was given for the "Hydropol" product marketed by Romud whilst major mud control problems were experienced in using "Revert" produced by the Johnson division of U. O. P. It is the author's opinion that successful drilling with Revert would necessitate the presence of on site personnel qualified to carry out continual testing of the mud which would need to include chemical analyses.

2.7.2 Experimental Testing

The muds used in the experimental testing included a straight bentonite (Aquagel) and a bio-degradable polymer low solids product (Hydropol). Both muds when used were mixed according to manufacturer's recommended figures.

The Aquagel mud was mixed in fresh water at a concentration of approximately $6\frac{1}{2}\%$ by weight. Over a wide range of tests the mud properties were as follows:-

Marsh funnel viscosity = 46-48 seconds

API Filtrate Loss

30 min. Corrected Volume = 8 - 8.4 cc
(Negligible initial spurt)
Filter cake thickness = 1/32" - 2/32"

No rheological measurements were taken on any of the Aquagel muds when tested since a suitable multispeed viscosimeter was not available. The particle size distribution of the Aquagel mud solids was evaluated by Hydrometric analysis and is shown in Figure 5.

The recommended concentrations for use of a Hydropol mud system are between 0.3 and 0.9%. A common complaint from drillers when using the original Hydropol was that it was not thick enough. Recently, Romud have greatly increased the viscosity of Hydropol resulting in a mud with which drillers should be far happier. It should be pointed out that the batch of new product Hydropol supplied for use in testing was far more viscous than the manufacturer's claims. In fact funnel viscosities were 33, 49 and 90 seconds for concentrations of 0.3, 0.6 and 0.9% by weight respectively. Romud claim that in future quality control will be more rigid. However, the necessity for possible preliminary on site evaluation and subsequent care in mudding up should be stressed.

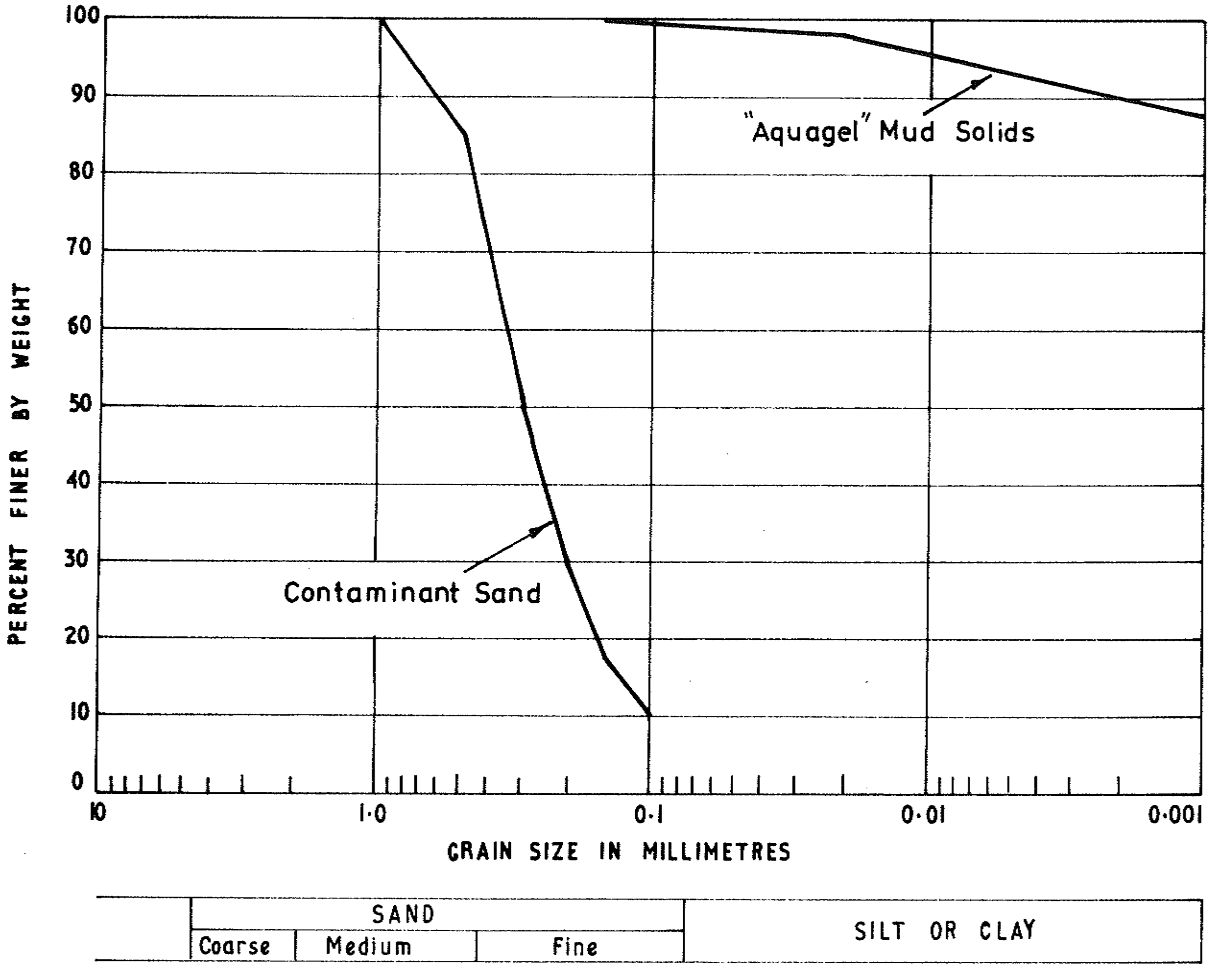
Laboratory pilot testing of Hydropol mud properties was carried out. The results are summarised in Table 1.

Table 1: Hydropol Mud Pilot Testing

Mud	Marsh Funnel Viscosity (seconds)	A.P.I. Filtrate Testing			Plastic Viscosity (cps)	Yield Point (lb/ 100 sq.ft)
		Corrected Volume (cc)	Initial Spurt (cc)	Filter Cake thickness		
Old						
0.3%	28	14	25	Nil	2-3	0
0.6%	30	17	29	Nil	5	0
0.9%	33	12	40	Nil	6	5
New						
0.3%	33	14	42	Nil	6	7
0.6%	49				13	26
0.9%	90	11	18	Nil	>15	>30

As can be seen the major effect of the product change is an increase in both the plastic viscosity and the yield point. Experimental circulation testing was carried out using both the old and the new more viscous Hydropol.

The mud circulating past the exposed aquifer formation will contain cuttings and solids which have not been removed at the surface. Quite often sand will not be removed from the mud by settling in the surface pits and/or mechanical separation. In a typical bore being



CONTAMINANT SAND:

Sand as carried at 6% by weight by a 10 lb./U.S gallon mud in a typical hole being drilled in unconsolidated material in New South Wales.

FIGURE 5: GRAIN SIZE DISTRIBUTIONS OF TEST MUD SOLIDS.

drilled in unconsolidated material near Dubbo, N.S.W., a sand content of 6% by weight was carried by a 10 lb/US gallon mud. A sample of this sand was taken from the mud and its grading determined and plotted in Figure 5. Tests were carried out for both the Aquagel and Hydropol mud systems wherein controlled solids contamination of the mud system was introduced in the form of specified percentages of a sand prepared to the grading shown in Figure 5.

2.8 Test Program

It was intended to look at a far wider range of variables. However, as is often the case with an experimental program, unforeseen difficulties arose and the program was of need modified for completion within the time limit of the project.

The tests completed, reported and analysed are summarised in Table 2.

Table 2 Mud Circulation Test Summary

Test	Aquifer Materials	Mud Velocity (ft/min)	Mud Pressure (psi)	Dynamic Exposure Time (mins)	Mud System (Percentages by weight)	Marsh Viscosity (seconds
001	1,2,3,4	120	20	10	6% Bentonite	48
002	1,2,5,6	120	21	300	$6\frac{1}{2}$% Aquagel	48
003	2,3,4,6	100	11	205	$6\frac{1}{2}$% Aquagel	46
004	2,3,6, 3/16" Pea	125	21	250	$6\frac{1}{2}$% Aquagel	48
005	2,3,4,6	120	12	180	($6\frac{1}{2}$% Aquagel (+ 6% Sand	50
006	2,3,4,6	120	21	70		56
007	Attempted test of lime affected Aquagel mud system was abandoned					
008	1,2,3,6	100-140	8-14	150	(0.9% old (stock (Hydropol	36
009	1,2,3,6	120	20	150		34
010	1,2,3,4	130	20	40	0.6% New Hydropol	45
011	1,2,3,4	100-130	12-28	120	0.6% New Hydropol + 6% Sand	52

3. Results and Discussion

3.1 General

Full results and observations for all tests are set out in Appendix V. A summary of the tests carried out is given in Table 2.

The development of both internal and external filter cakes, depths of mud invasion, ease of removal of filter cakes and the degree of permanent formation damage within the invaded zone have all been studied.

The discussion presented here is largely subjective and based on the author's interpretation of the experimental results. Lack of basic understanding of the clogging and unclogging processes for clay and polymer based fluids in granular materials precludes a more quantitative and objective analysis.

Guidelines are offered for the expected behaviour of aquifer materials when exposed to certain drilling mud systems.

3.2 Notation

D_x and d_x will denote the particle diameters at x per cent finer than for the aquifer material and the mud solids respectively.

In many tests formation damage was recorded for the material within the invaded zone. Values quoted for formation damage are given as the percentage reduction in permeability from the original unexposed aquifer material value.

3.3 Bentonite Base Mud Systems

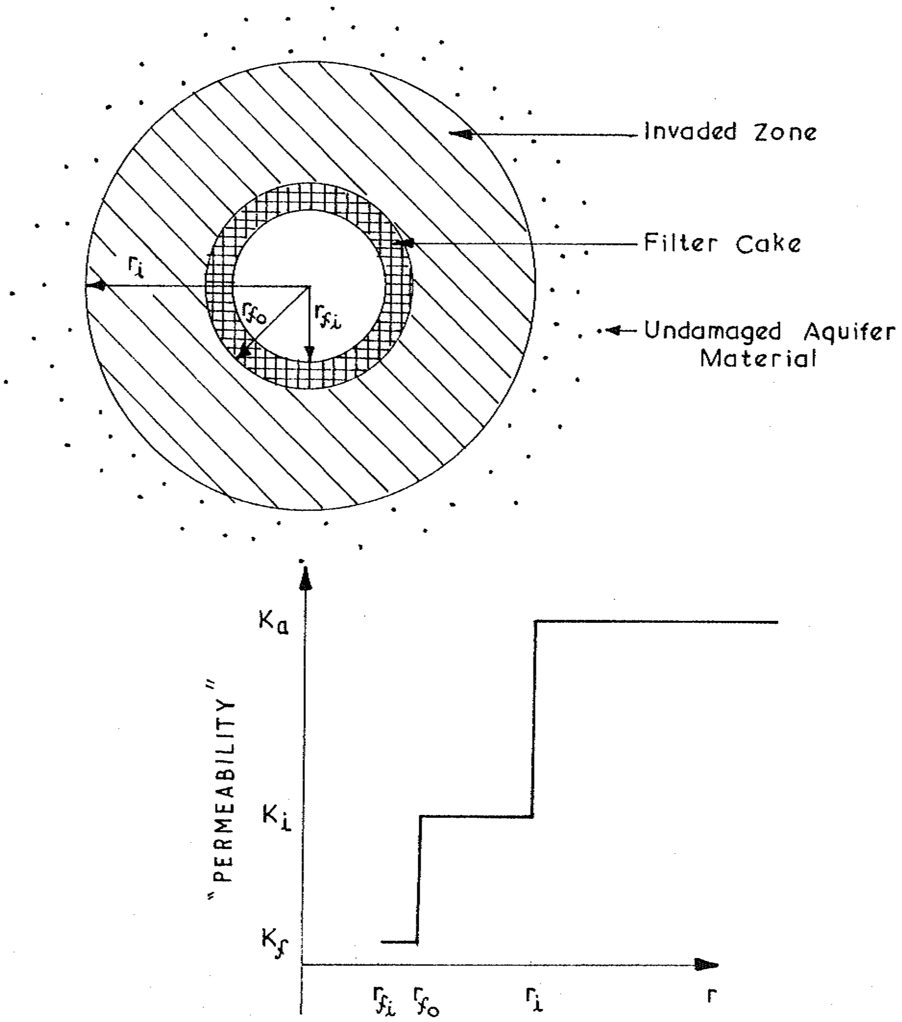
3.3.1 General

The development of both external wall cakes and internal filter cakes was illustrated in the test results. In some instances no filter cake developed at any position within the aquifer material and whole mud flowed freely from the sample (i.e. lost circulation).

The depths of mud invasion were calculated from the volume of fluid collected below the samples.

Formation damage (reduction in permeability) to the aquifer material within the invaded zone (as distinct from the filter cake) occurred during exposure to the mud flow. Partial recovery of the permeability of the invaded material was achieved by water flushing. However, residual permanent formation damage which could not be removed by continued and extensive water flushing at hydraulic gradients as high as 30 was recorded. The permanent reductions in permeability of the material within the invaded zone were quite significant (in extreme cases as high as 90%).

The formation damage did not vary gradually with distance from the exposed material surface. Rather, uniform damage was found throughout any homogeneous material layer within the invaded zone. This result should be of particular interest to geophysicists in interpreting well logging data in unconsolidated aquifers. Although experiments were only carried out for conditions of one dimensional flow, it is the author's opinion that the form of damage within the invaded zone would still be uniform under radial flow conditions.



NOTATION:

r_{fi} – inside radius of filter cake
r_{fo} – outside radius of filter cake
r_i – radial extent of invaded zone
K_f – permeability of filter cake
K_i – permeability of invaded zone
K_a – permeability of aquifer material

FIGURE 6: SCHEMATIC DISTRIBUTION OF FORMATION DAMAGE NEAR A WELL - BENTONITE MUD

The variation of permeability in the vicinity of a newly drilled hole in an homogeneous aquifer is shown in Figure 6. The schematic representation clearly differentiates between the filter cake, the invaded zone and the unaffected aquifer material.

3.3.2 Aquifer-Mud Interaction, Behaviour Categorisation in Terms of Sealing Mechanism

The interactive behaviour of an aquifer material with a bentonite base mud may be thought of as belonging to one of three categories:

Category 1. External Wall Cake

(Reference: Appendix V5, V6 - Material 2,6). An external wall cake builds up above the exposed aquifer surface. This cake is of the order of 5 to 20 mm in thickness. During the initial stages of development the cake undergoes cyclic erosion and reformation. A stable wall cake eventually results after mud flow exposure times of between 5 and 60 minutes.

The stable wall filter cake is not impervious, and filtration loss to the aquifer material continues at a small but steady rate. Mud invasion depths may be large due both to the time taken to effect a stable cake and the continued filtration losses. Test results indicate an approximate invasion rate of 30 mm/hour/unit area through the stable wall cakes developed during this test program.

The wall cakes may in some cases be broken by, but not completely removed by the application of direct water pressures of less than 25 psi.

Permanent damage to the aquifer material within the invaded zone is considerable. This is probably due to the invasion of the aquifer by the finer particles of the suspended mud solids. The finer mud solid particles are small enough to pass through the wall filter cake. (87% of Aquagel mud solids are finer than 1 micron - Figure 5).

Category 2. Internal Filter Cake

(Reference. Appendix V2, V3, V4 - Material 1,2,5
Appendix V5, V6 - Material 3,4)

An internal filter cake develops almost immediately (within $\frac{1}{2}$ minute) after exposure to the mud flow. The filter cake develops from internal bridging of mud solids within the pores of the aquifer material and generally forms within the top 10 mm of the aquifer material. The internal cake is very distinct and impervious, thus preventing any further loss of mud filtrate.

In the short period prior to the formation of the internal filter cake, some invasion of the aquifer takes place. The depth of mud invasion is relatively small, and dependent upon the mud differential pressure and the aquifer material permeability. The most severe result obtained was an invasion depth of 390 mm in the $\frac{1}{2}$ minute prior to internal filter cake development during test 006 (Material 4, K = 1500 mm/min).

The material within the invaded zone (as distinct from the internal filter cake) suffers permanent damage. The permanent damage is generally less than that for invaded material where an external wall cake forms.

The internal filter cake is difficult to break by the application of direct water pressure above the exposed surface. In selected trials, internal cakes were easily broken by a small diameter low velocity water stream played directly against the material surface. Development by jetting techniques should therefore be effective in breaking up internal filter cakes formed close to the exposed aquifer surface as is normally the case.

Category 3. Lost Circulation

(Reference. Appendix V3 - Material 4). No filter cake is formed and whole mud flows freely into the aquifer material when the material pores are too large for any internal bridging of mud solids to occur.

The material within the extensive invaded zone is, however, easily flushed clean of mud by low velocity water flow. Negligible permanent formation damage results.

Between each category there is a transition zone where the behaviour may be expected to progressively change from one category to the next.

Transition 1 - 2

It is conceivable that both internal and external filter cakes may develop simultaneously within the transition between categories 1 and 2.

Transition 2 - 3

At the lower values of material permeability within the transition between behaviour categories 2 and 3, internal filter cakes can be expected to develop within the top 10 mm of the aquifer. The time of mud exposure necessary for the complete development of such an impervious internal filter cake, and hence the depth of invasion, will increase with material permeability. The removal of any internal cake so formed, should become progressively easier with a more permeable aquifer material.

At higher values of permeability within the transition, whole mud can be expected to flow into the aquifer. The invading mud should be readily flushed from the aquifer during development. However, permanent formation damage to the material may be a possibility until the material behaviour can be safely termed category 3.

As a guide to behaviour within the transition 2-3, the results of tests 003 and 004 for material 3 will now be summarised:

Material } K = approx. 600 mm/min, $b/a^2 = 0.24$
Properties } D_{10} = 1.3 mm, $D_{60}/D_{10} = 1.3$

An impervious internal filter cake took 10 minutes to form within the top 10 mm of the material. Prior to cake formation, considerable mud invasion of the aquifer took place. Invasion depths of 6 metres and 16 metres at respective mud pressure differentials of 11psi and 21 psi were estimated.

In test 003 the internal cake could not be broken by direct water pressure of 15 psi whilst in test 004 the cake was brken by a pressure of only 5 psi. Permanent damage within the invaded zone was 10-35%.

3.3.3 Uniform Aquifer Materials - $D_{60}/D_{10} < 1.5$

Although the majority of aquifers are well graded, the bulk of results were obtained for samples of uniform unconsolidated aquifer materials (Figure 3). These materials being essentially one sized particles allowed a basic understanding of aquifer-mud interactions to be developed.

The results of tests on uniform aquifer materials exposed to pure and sand contaminated Aquagel mud systems are summarised in Figures 7 and 8 respectively. The divisions into the various behaviour categories as shown in these figures have been related to both the coefficient of hydraulic conductivity (K) and the effective diameter (D_{10}) of the material.

The results of Figures 7 and 8 may be referred to for a guide to the possible extent and degree of permanent formation damage likely to occur when drilling an aquifer with a bentonite based mud.

A typical classification of unconsolidated materials in terms of permeability is shown in Figure 9.

The sample materials tested in the mud circulation rig would all be classed as good aquifers.

Mud Invasion Depths

For category 2 behaviour (the immediate development of impervious internal filter cakes) the depth of mud invasion and thus the extent of permanent formation damage is shown in Figures 7 and 8 to increase with both mud pressure and aquifer permeability. The impervious internal filter cakes once developed prevent any further mud losses. Thus, the invasion depth is independent of the time of mud exposure.

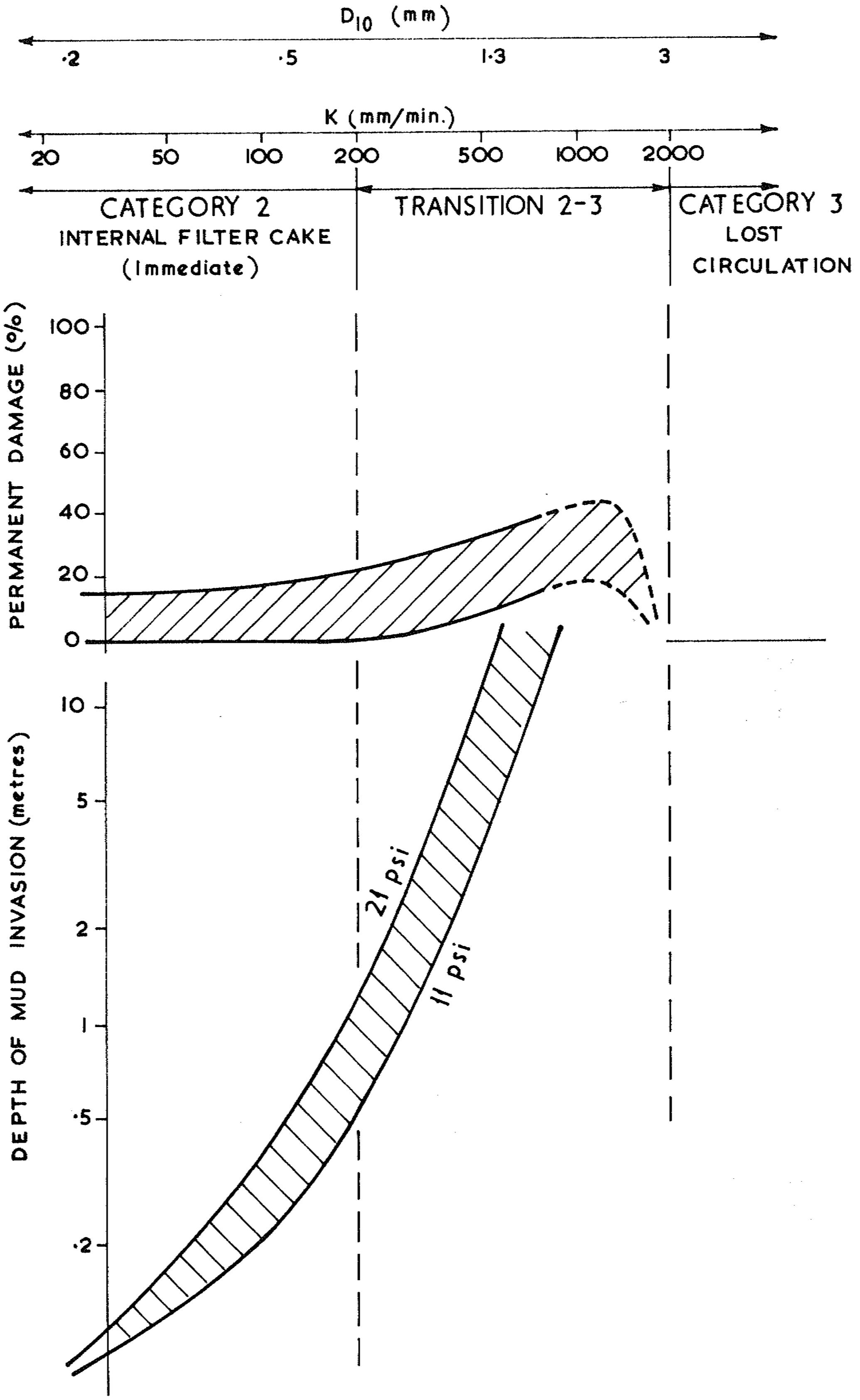


FIGURE 7: UNIFORM MATERIAL BEHAVIOUR $D_{60}/D_{10} < 1{\cdot}5$

Pure 'Aquagel' Mud (Tests 002, 003, 004)

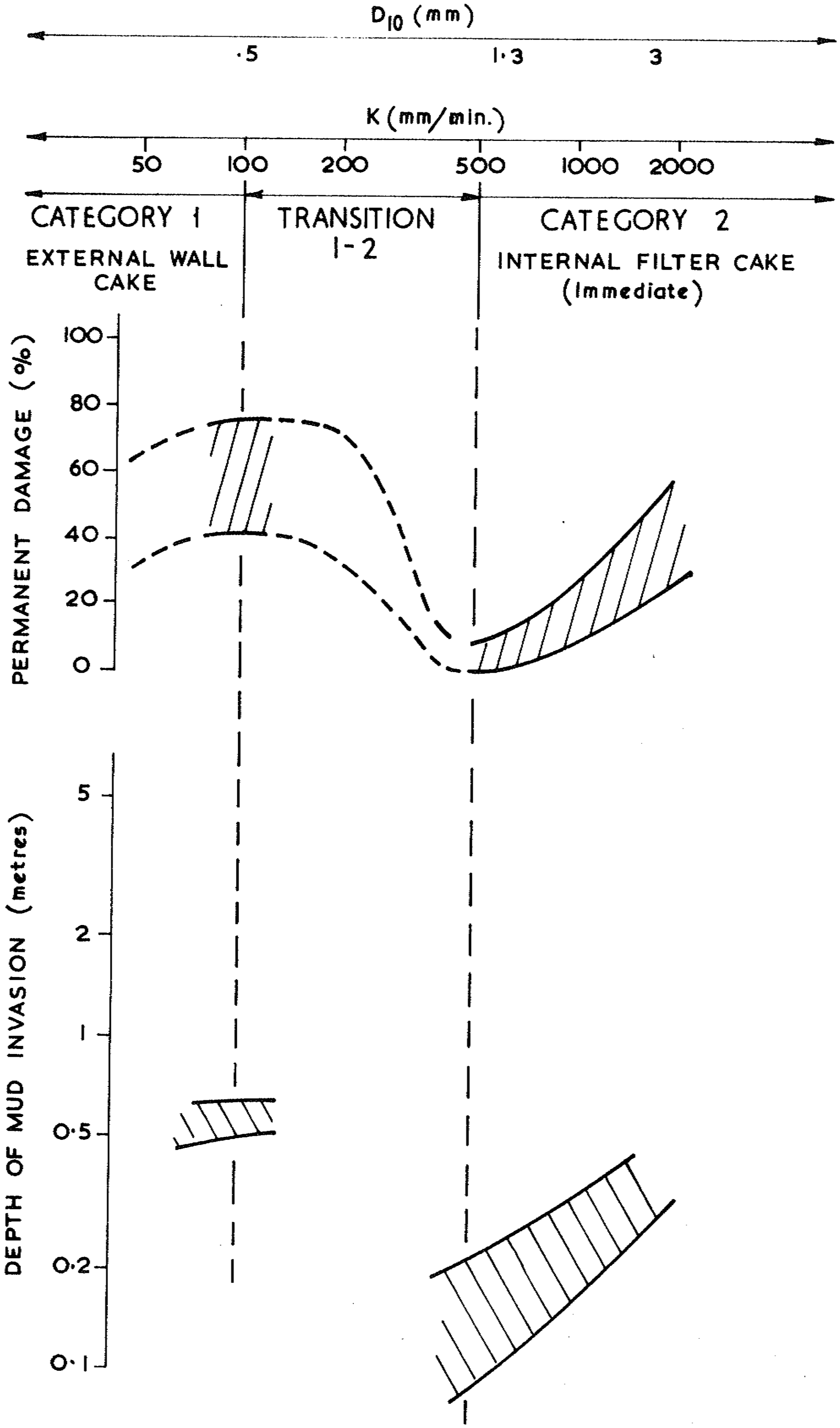


FIGURE 8: UNIFORM MATERIAL BEHAVIOUR $D_{60}/D_{10} < 1\cdot5$
Sand Contaminated 'Aquagel' Mud (Tests 005, 006)

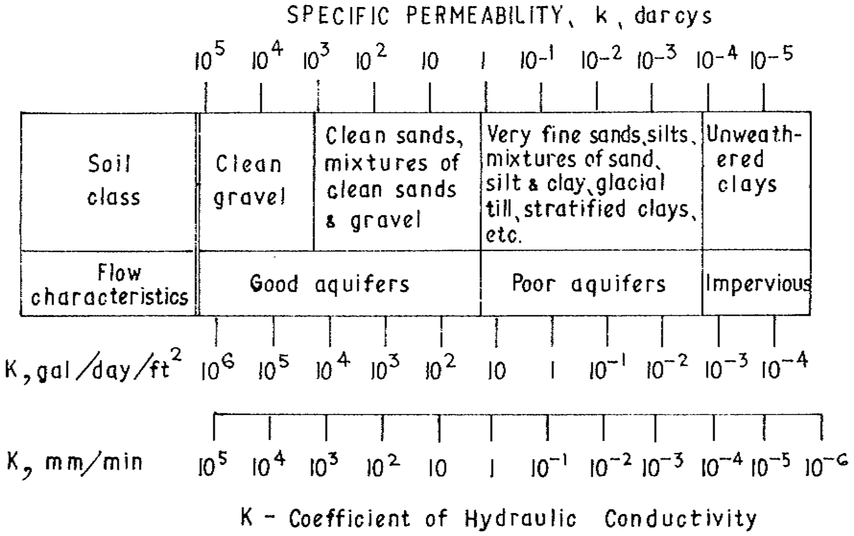


FIGURE 9: TYPICAL PERMEABILITIES FOR UNCONSOLIDATED MATERIALS

The invasion depths for category 1 behaviour (external wall cake) are illustrated by the results obtained using material 2 in tests 005 and 006 wherein after exposure times of 180 and 70 minutes the invasion depths were 600 and 400 mm respectively. The behaviour of materials which developed external wall cakes, was, however, characterised by a continued steady loss of mud at a rate of approximately 30 mm/hour/unit area. This loss rate through the developed stable external wall cake and into the aquifer material appeared independent of the mud pressure differential. With lengthy hole completion times, this continued mud invasion could lead to serious reductions in bore productivity resulting from an extensive invaded zone of permanently reduced permeability.

Severity of Permanent Formation Damage

Generally, the degree of permanent formation damage to materials which develop internal filter cakes (category 2) becomes more severe with increasing material permeability.

Permanent damage to materials which form external wall cakes (category 1) appears to be more severe than for materials characterised by internal filter cakes (category 2). However, the results for category 1 behaviour are limited and the validity of this statement is questionable.

3.3.4 Graded Materials $D_{60}/D_{10} > 2$

(a) Pure Aquagel Mud

Although the tests on graded materials were severely limited in extent, definite differences from the behaviour of the uniform materials ($D_{60}/D_{10} < 1.5$) were noted for the pure Aquagel mud tests:

(i) The upper bound value of permeability for category 2 behaviour (i.e. internal filter cake formation) is lower for a graded material than for a uniform material, the estimated bound for material 6 (D_{10}=0.5mm, D_{60}/D_{10} = 7.2) being 80 mm/min as compared to the value of 200 mm/min for uniform materials.

(ii) The lower bound value of permeability for category 3 behaviour (i.e. lost circulation) is approximately the same for both graded and uniform materials. If anything, the value should be lower for a graded material.

(iii) Permanent damage to the aquifer material within the invaded zone is more severe for a graded material than for a uniform material. In general this is particularly important for materials which fall within transition 2.3.

In all tests involving the well graded material 6 (D_{60}/D_{10} = 7.2) reported permanent damage within the invaded zone was frequently of the order of 80-90% for original material permeabilities in the range 40-310 mm/min.

(b) Sand Contaminated Aquagel Mud

Results for graded materials were limited to tests 005 and 006 using material 6. External wall cakes developed in time for sample material permeabilities of 80 and 125 mm/min. at the exposed surface. The steady loss of mud through the stable wall cakes was once again of the order of 30 mm/hour/unit area. Permanent formation damage within the invaded zone was severe and increased with permeability. The results are inconclusive but will be summarised here as an indication of the relative magnitudes of possible permanent damage.

Test	Mud Pressure psi	Exposure Time minutes	Invasion Depth metres	K (Original) mm/min	Permanent Damage
005	12	180	1.1	80	25-50%
				15	0-10%
006	21	70	0.6	125	75-85%
				25	50-70%
				18	40-60%

The damage appears less severe than that reported for pure Aquagel mud exposures in which internal filter cakes were formed within material 6.

The complexity of the behaviour of a graded aquifer material is clearly illustrated by the variability of the results.

3.3.5 Guidelines

The main factors affecting the interaction between an unconsolidated aquifer material and a bentonite base mud system are:-

(i) particle size distribution of mud solids,
(ii) pore size distribution of aquifer material,
(iii) plastering ability of the mud.

A consideration of filter pack selection criteria, the theory of bridging of solid particles, and experimental results from the tests conducted during this investigation, has led to the formulation of the aquifer-mud behaviour chart shown in Figure 10.

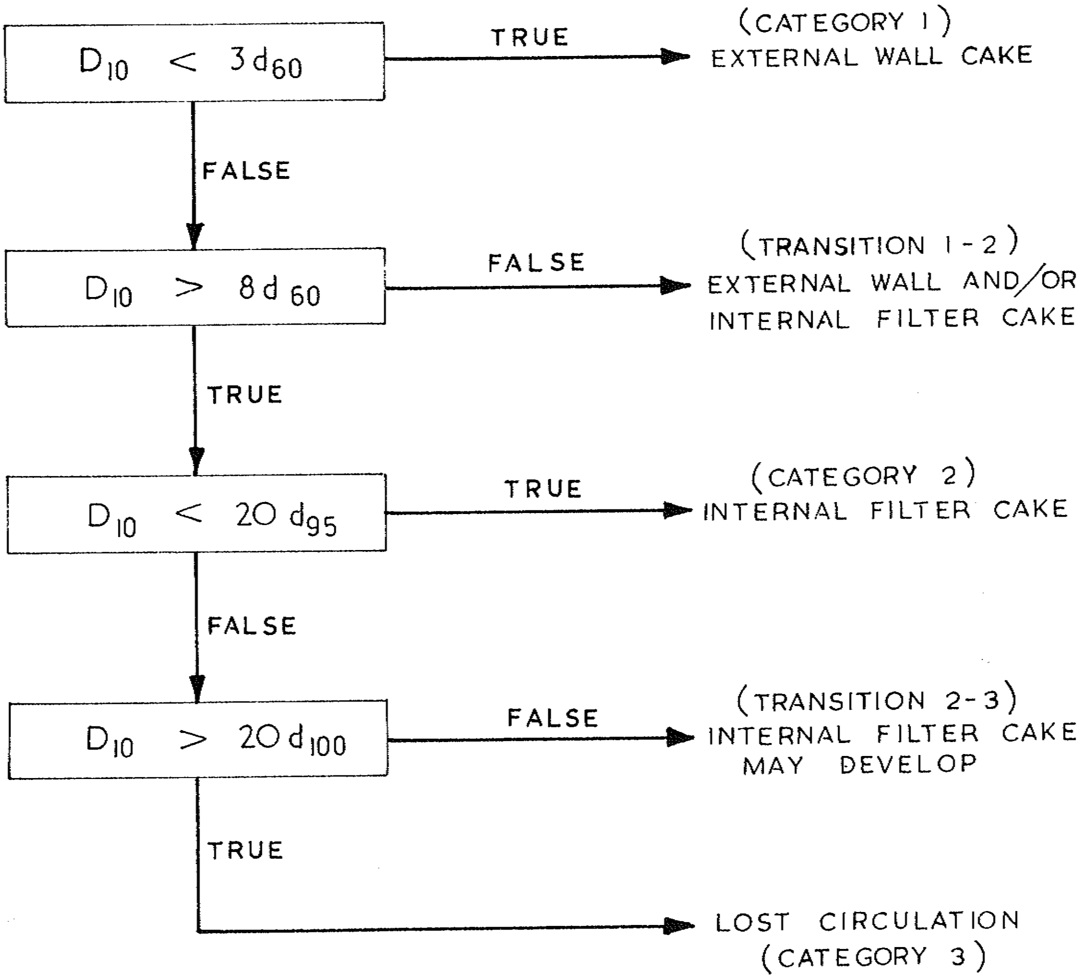


FIGURE 10: BENTONITE BASE MUD - AQUIFER INTERACTION CHART

To minimise both the extent and degree of permanent formation damage the immediate development of an impervious internal filter cake just below the exposed aquifer surface would appear the optimum.

A suggested criterion for this desired category 2 behaviour can be stated:

$$8d_{60} < D_{10} < 20\,d_{95}$$

The impervious filter cake formed in this way can be expected to occur within the first 10 mm.of the aquifer material.

Although this type of filter cake proved difficult to remove by direct pressures during laboratory tests, backwashing, chemical treatment, and in particular jetting during development should be effective in breaking and removing this thin but tough and impervious internal filter cake.

3.4 Hydropol Base Mud Systems

3.4.1 General

The interactive behaviour of the Hydropol mud systems with the various aquifer test materials was different to the behaviour exhibited in the previously described test results for bentonite base muds.

The pure Hydropol mud (tests 008, 009 and 010) contained no solid particles and as such, any filter cake formed could only be attributed to the "plastering ability" of the mud. For finer aquifer materials distinct, plastic, cohesive 1 mm thick filter cakes were formed at the exposed surface whilst lost circulation was a problem with the more permeable samples.

The sand contaminated Hydropol mud system (test 011) behaved similarly to the bentonite-sand mud (tests 005, 006) in forming both external wall cakes and internal filter cakes with different test aquifer materials.

Filter cakes developed by the Hydropol mud systems were less impermeable than those formed using bentonite based muds and as such were less effective in limiting filtration loss to the aquifer material samples.

Formation damage to the aquifer material within the invaded zone (as distinct from the filter cake) occurred and was of a severity comparable to that exhibited in tests with bentonite base muds. Partial recovery of the permeability of the invaded material was possible by extensive water flushing at high hydraulic gradients. The residual permanent formation damage even after such treatment was often quite severe (frequently above 50% and in extreme cases as high as 95%).

The recommended P.B.D. breakdown solution proved extremely effective in disintegrating and dispersing any filter cakes formed by the Hydropol mud system at the exposed material surface.

However, P.B.D. treatment was in the main only marginally more effective than water flushing in rehabilitation of the aquifer material within the invaded zone (beyond the filter cake). For one particular aquifer material (material 2), further formation damage within the invaded zone occurred consistently after P.B.D. treatment.

The failure of the P.B.D. to restore permeability within the invaded zone will now be discussed.

The viscosity and gel strength of a Hydropol solution can be quickly destroyed by the addition of P.B.D., the breakdown being effected by an enzyme within the P.B.D. which acts upon the viscosity building Hydropol polymers. This ability to destroy the Hydropol gel structure would imply that P.B.D. treatment should be quite successful in rehabilitation of the invaded zone. Test results clearly contradict such implied behaviour. The author offers the following explanation: On a microscopic scale the long chain molecules of the Hydropol polymers envelop individual aquifer material grains and are held firmly to such grains by molecular forces in such a manner that no reaction with the P.B.D. enzymes can take place. The Hydropol mud within the pores of the material is not so firmly held to the grains and can be removed by either water back flushing or breakdown by P.B.D. with almost equal success.

Thus, development of the invaded aquifer material would appear limited to removal of the Hydropol mud from within the pores of the material matrix. The resultant formation damage as indicated by test results may be severe and quite extensive.

It might be argued that with time this damage will decrease when the Hydropol deteriorates and loses its viscosity. This seems unlikely since pilot testing revealed the Hydropol to satisfy the manufacturers claims in being quite stable over long periods of time.

3.4.2 Uniform Materials - Pure Hydropol Mud

(Reference: Appendix V8, V9, V10 - Material 1,2,3,4).

The results of tests on uniform aquifer materials ($D_{60}/D_{10} < 1.5$) exposed to pure Hydropol mud including both old and new stock products are summarised in Figures 11, 12 and 13.

Old Stock Hydropol (Figures 11, 12)

With the lower permeability materials (1 and 2) a distinct thin 1 mm plastic cohesive filter cake was developed at the exposed surface. This filter cake was difficult to remove by water flushing alone, but easily dispersed when treated with P.B.D.

The non-distinct low permeability layer which formed in the top 3mm of the more permeable material 3 sample was easily rejuvenated by water flushing alone.

Permanent damage to the aquifer material invaded by the Hydropol mud was both more severe and more extensive than was reported in earlier tests involving pure bentonite base muds. P.B.D. treatment had surprisingly little success in rehabilitation of the invaded zone material. Both the extent of mud invasion (estimated by the

17

volume of mud filtrate collected below the sample), and the severity of the permanent formation damage increased with material permeability and the mud differential pressure (Figures 11, 12, 14).

This behaviour was as expected in regards to the extent of mud invasion. The extrapolation of such a trend for the severity of the formation damage beyond the range of the experimental results would however be considered dubious.

In some cases the formation damage varied gradually with distance from the exposed surface whilst in others uniformly damaged material layers were present within the invaded zone.

New Hydropol (Figure 13)

No distinct cohesive plastic filter cakes were formed with the more viscous Hydropol. Rather, 1-5mm thick non-distinct layers of low permeability developed at the surface of materials 1 and 2. Water flushing alone was reasonably successful in overcoming the flow blockages caused by such layers. Complete breakdown of these low permeability layers at the sample surfaces was more easily and quickly achieved by the addition of P.B.D.

The more viscous new Hydropol mud appeared to significantly reduce both the severity and extent of formation damage previously obtained using the old stock product (Figures 13, 14). P.B.D. treatment was again of only minor beneficial value in attempts to rehabilitate material within the invaded zone.

Permanent damage was of the same order of severity but still more extensive than with a pure bentonite mud.

In all cases uniform damage was found to occur in homogeneous material layers within the invaded zone.

Note:

In all tests using Hydropol mud systems additional formation damage was reported after P.B.D. treatment of material 2. The incremental reduction in permeability resulting from P.B.D. treatment was as high as 30%. No explanation for this behaviour can be offered by the author.

3.4.3 Uniform Materials - Sand Contaminated Hydropol Mud

(Reference: Appendix V11 - Material 1, 2, 3, 4)

Hydropol when used in the field will not be pure. Solids contamination of the pure mud by cuttings from the hole will occur. Test 011 was carried out to examine the possible behaviour of a more realistic solids contaminated new product Hydropol mud. Figure 15 summarises the results of test 011.

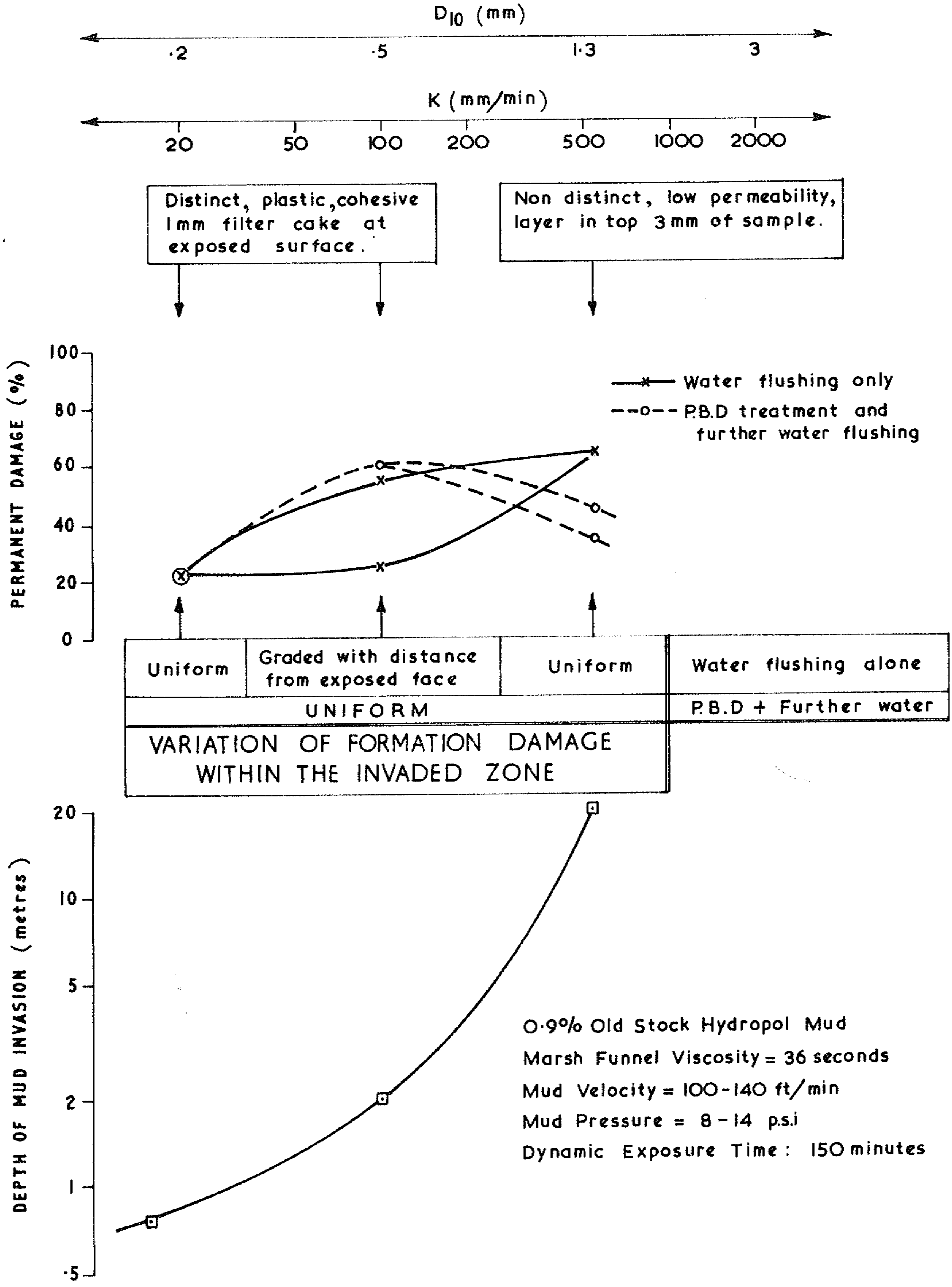
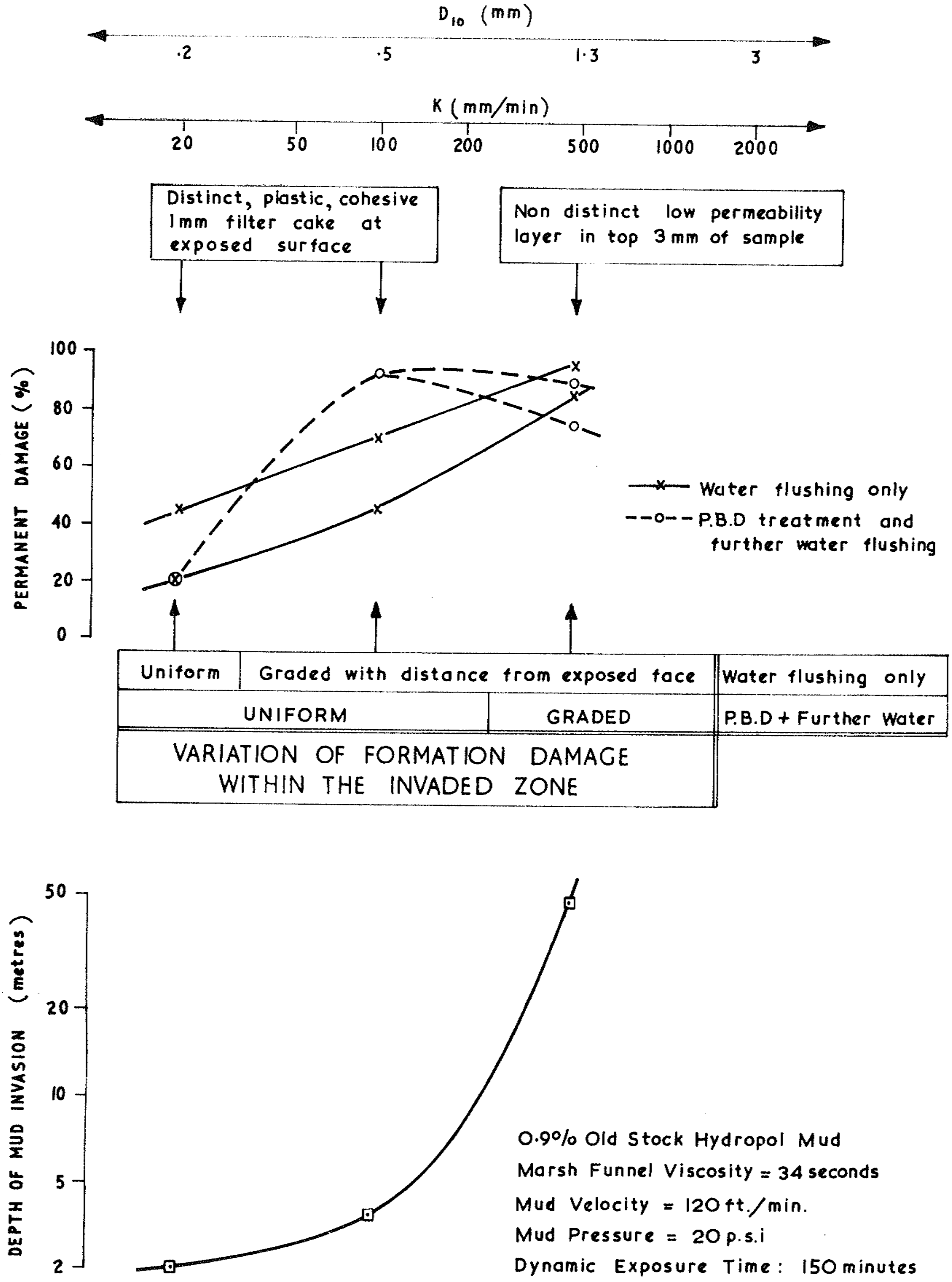


FIGURE 11: UNIFORM MATERIAL BEHAVIOUR $D_{60}/D_{10} < 1{\cdot}5$

PURE HYDROPOL (OLD STOCK) TEST 008



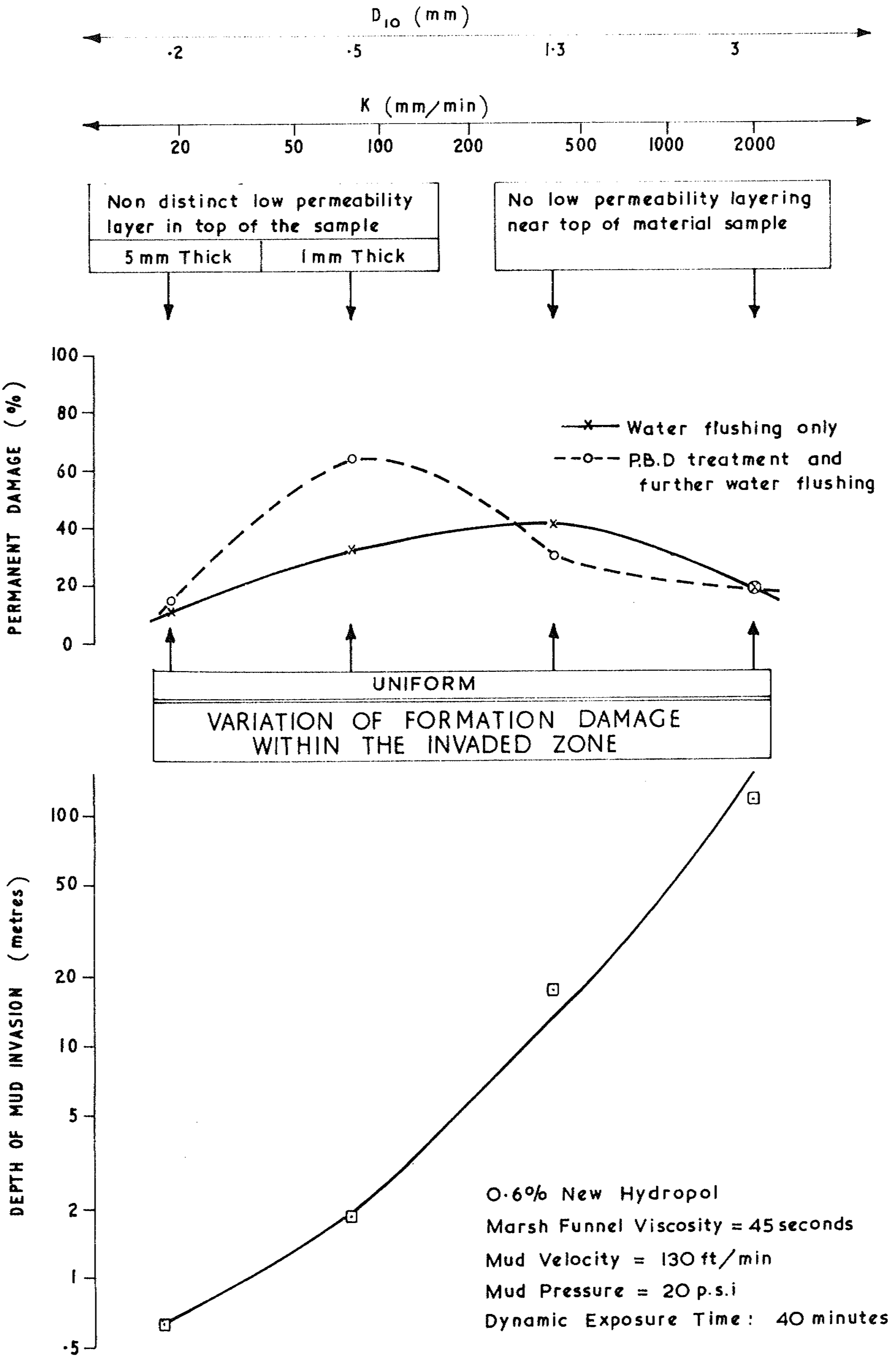
Distinct, plastic, cohesive 1mm filter cake at exposed surface

Non distinct low permeability layer in top 3 mm of sample

0·9% Old Stock Hydropol Mud
Marsh Funnel Viscosity = 34 seconds
Mud Velocity = 120 ft./min.
Mud Pressure = 20 p.s.i
Dynamic Exposure Time : 150 minutes

FIGURE 12: UNIFORM MATERIAL BEHAVIOUR $D_{60}/D_{10} < 1{\cdot}5$

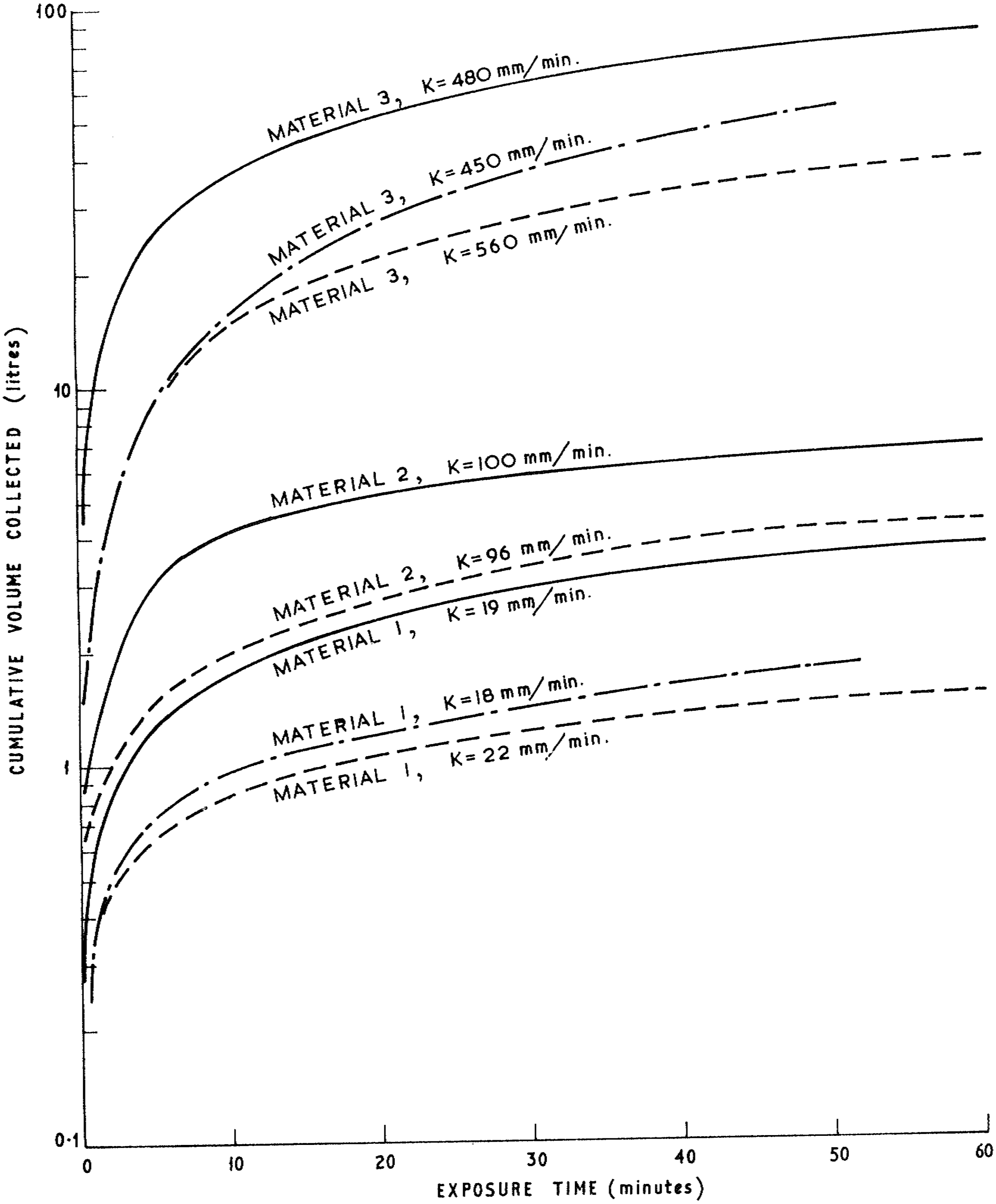
PURE HYDROPOL (OLD STOCK) TEST 009



0·6% New Hydropol
Marsh Funnel Viscosity = 45 seconds
Mud Velocity = 130 ft/min
Mud Pressure = 20 p.s.i
Dynamic Exposure Time : 40 minutes

FIGURE 13: UNIFORM MATERIAL BEHAVIOUR $D_{60}/D_{10} < 1{\cdot}5$

PURE HYDROPOL (NEW) - TEST 010.



LEGEND:

	TEST	MUD VELOCITY (ft/min)	MUD PRESSURE (p.s.i)	MARSH FUNNEL VISCOSITY (seconds)	HYDROPOL MUD
— — — — —	008	100 - 140	8 - 14	36	0·9% Old Stock
————	009	120	20	34	
—·—·—	010	130	20	45	0·6% New Stock

FIGURE 14: EXTENT OF HYDROPOL MUD INVASION - EFFECT OF MUD PRESSURE, MUD CONCENTRATION AND MATERIAL PERMEABILITY

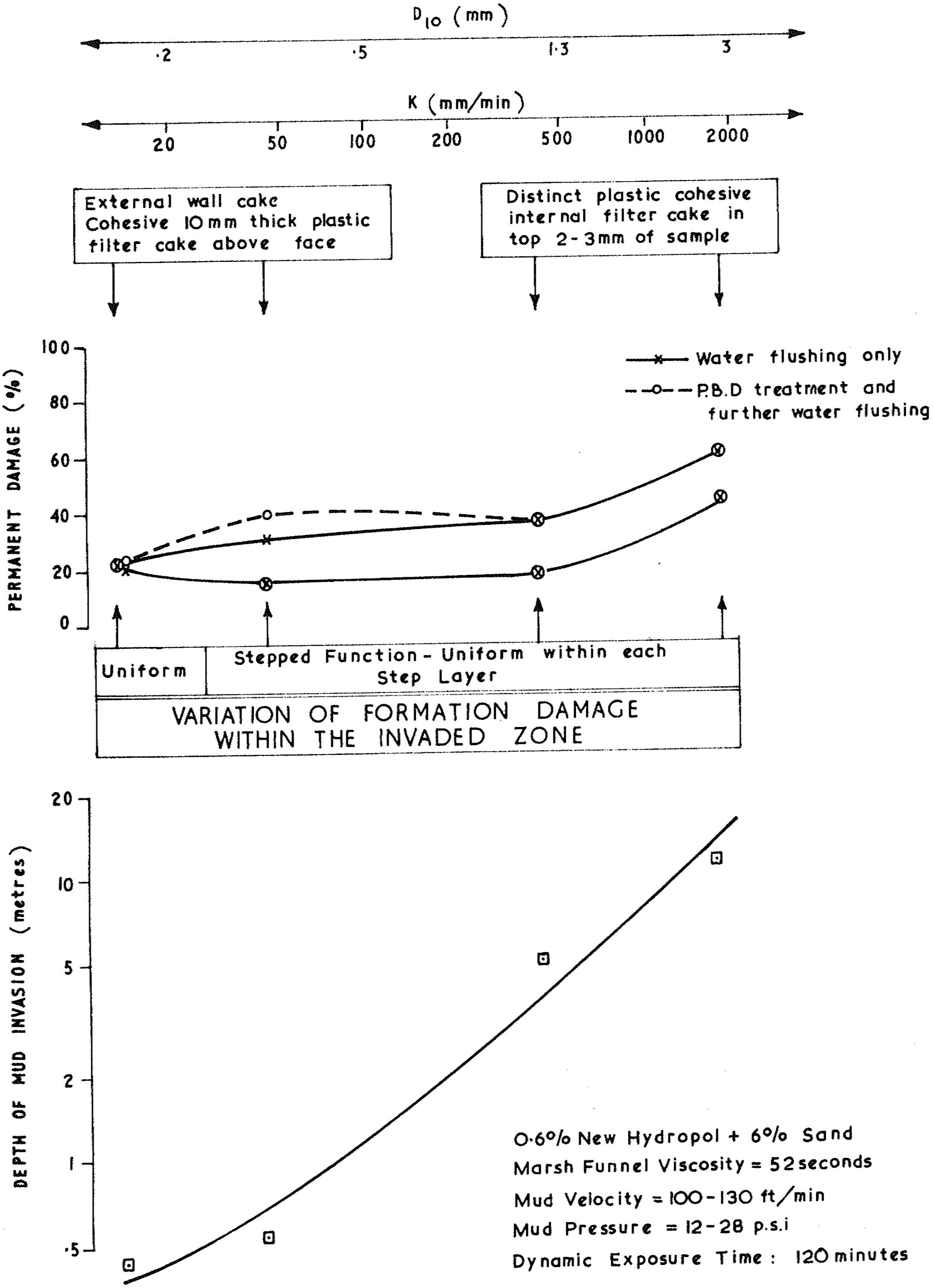


FIGURE 15: UNIFORM MATERIAL BEHAVIOUR $D_{60}/D_{10} < 1.5$

SAND CONTAMINATED HYDROPOL MUD-TEST 011

The interactive behaviour of this mud with the aquifer materials was similar to that exhibited during tests with sand contaminated bentonite mud systems (tests 005, 006).

External 10 mm wall cakes built-up above the exposed face for the less permeable materials (1 and 2) whilst distinct internal filter cakes were formed with the more permeable materials (3 and 4). The filter cakes so formed although more effective in limiting filtration loss to the aquifer samples than those developed by pure Hydropol muds were still not as impermeable as bentonite mud filter cakes.

The filter cakes were plastic cohesive layers of Hydropol and sand. During development it is possible that large proportions of the external wall cakes may be removed en masse as cohesive entities. P.B.D. treatment was quite effective in destroying the viscosity of the Hydropol mud component of all filter cakes. However, the removal of the contaminant mud solids trapped within any filter cake must be achieved by physical means, as is the case with bentonite base muds.

The extent of the mud invasion was less than that for a pure Hydropol mud system but was still more than for a bentonite-sand mud.

For materials with permeabilities less than 500 mm/min the formation damage was of the same order as that for a pure new Hydropol mud. For more permeable materials the damage from the sand contaminated Hydropol was more severe. It would appear that with the more permeable materials the invasion of solid mud particles becomes the more important cause of permanent formation damage. The severity of aquifer formation damage for the sand-Hydropol mud was of the same order as that for the sand-bentonite muds.

P.B.D. treatment was of minimal benefit in aiding the recovery of permeability of material within the invaded zone (beyond the filter cake).

The formation damage did not vary gradually with distance from the exposed face. Uniform damage within homogeneous material layers was found throughout the mud invaded samples.

3.4.4 Graded Materials $D_{60}/D_{10} > 2$

(Reference: Appendix V8, V9 - Material 6)

Tests carried out using graded materials were limited to the behaviour of material 6 (D_{10} = 0.5mm, D_{60}/D_{10} = 7.2) subjected to exposure from pure old stock Hydropol mud (Tests 008 and 009). The tested samples of the graded material 6 had various layers of differing permeability throughout their length. This layering of the test samples made clear interpretation of the results difficult. Definite behavioural trends were however noted.

The old stock Hydropol appeared to be capable of forming relatively impermeable filter cakes for layers of material 6 with permeabilities less than 40 mm/min.

The loss of mud filtrate through such cakes and hence the extent of mud invasion was less than that which occurred with the uniform materials. The difficulty in removing filter cakes developed at some distance from the hole in inhomogeneous aquifer materials was clearly illustrated in these tests. The filter cakes were formed at a distance greater than 100 mm from the sample surface. At such a distance from the exposed face, breakdown of the filter cakes by either water flushing and/or P.B.D. treatment was virtually negligible.

The inability of P.B.D. treatment to significantly aid in recovery of the invaded zone was again recorded.

Permanent formation damage was more severe than for the uniform aquifer materials. Permanent damage within the invaded zone was of the order of 95-70% for original permeabilities in the range 20-140 mm/min.

3.4.5 Guidelines

One of the main claimed advantages of a Hydropol mud system over a bentonite base mud for water-well drilling is the degree of protection offered to the aquifer material.

The experimental investigation seriously places such a claim in jeopardy for the following reasons:-

1. The filter cakes formed by Hydropol muds were less impermeable than those developed by bentonite muds. The depth of mud invasion of the aquifer formation around the drilled hole would thus be more extensive with a Hydropol mud.

2. P.B.D. treatment was quite effective in breaking down and dispersing filter cakes in the vicinity of the exposed aquifer surface, but was of little benefit in recovering the permeability of material within the invaded zone (beyond the filter cakes near the exposed surface).

3. The residual permanent formation damage within the invaded zone was of the same order for both Hydropol and bentonite base mud systems. This permanent damage may be quite severe for the commonly occurring well graded aquifers (damage possibly as high as 90%).

The decision to use a Hydropol mud rather than a common bentonite based system should thus not be based on the belief that formation damage will be reduced.

However, other factors such as ease of mixing and maintaining the mud, ease of removal of filter cake using P.B.D. and the reduction in the weight of material to be transported may justify its use. Generally mud material cost is small in relation to the overall hole completion costs and is not a major factor in the selection of a mud system.

The results of Figures 11, 12, 13 and 15 may be referred to for a guide to the possible extent and degree of permanent formation damage likely to occur when drilling an aquifer with a Hydropol mud.

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Appendix V

Mud Circulation Rig - Test Results and Observations

General

A series of experimental tests was carried out in which drilling muds were circulated past the exposed surfaces of unconsolidated aquifer material samples under various flow conditions.

Detailed descriptions of the mud circulation rig, procedures and related aspects of the test program are given in the main text.

Two basic mud systems were tested - straight bentonite clay base mud (Aquagel) and a bio-degradable low solids polymer mud (Hydropol).

The grading of the solids in the Aquagel mud is shown in Figure 1. 1.

Pure systems and deliberately solid contaminated systems of both muds were tested. The solids contamination was from a controlled content of a prepared sand. The grading of this sand is shown in Figure 1.1.

Mud velocity past the face of the samples was of the order of 120 ft/min.

The pressure differential above the face of the aquifer material samples was in general maintained at either 10 psi or 20 psi. In some tests pressure surging occurred.

The gradings of the various unconsolidated materials exposed to mud during the test program are shown in Figure 1.1.

A summary of all tests carried out is given in Table 1. 1.

The detailed results and observations for each test are contained in separate sections of this appendix.

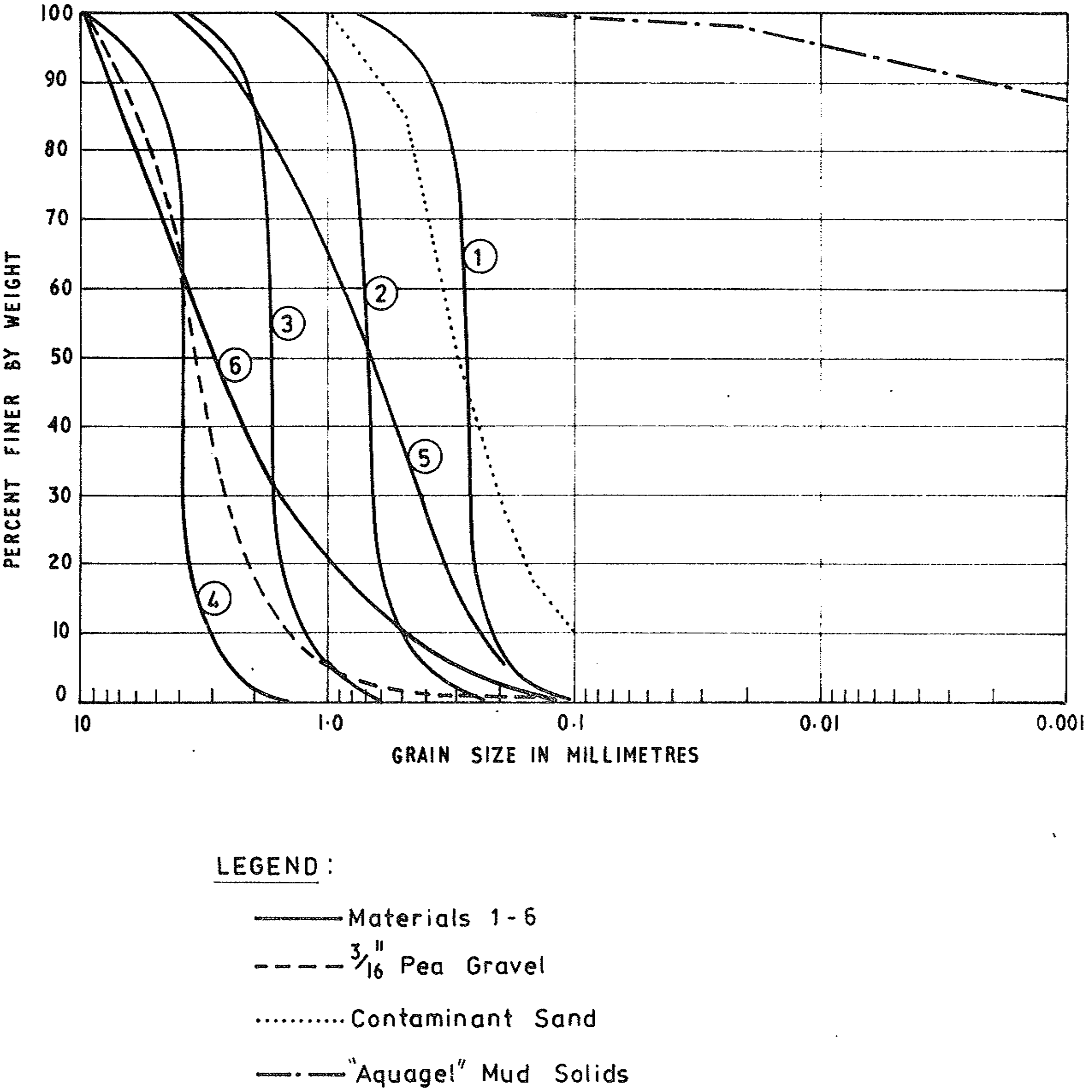


FIGURE 1·1 : GRAIN SIZE DISTRIBUTION FOR TEST AQUIFER MATERIALS AND MUD SOLIDS

Table 1.1 Mud Circulation Test Summary

Test	Aquifer Materials	Mud Velocity (ft/min)	Mud Pressure (psi)	Dynamic Exposure Time (mins)	Mud System (Percentages by weight)	Marsh Viscosity (seconds
001	1,2,3,4	120	20	10	6% Bentonite	48
002	1,2,5,6	120	21	300	$6\frac{1}{2}$% Aquagel	48
003	2,3,4,6	100	11	205	$6\frac{1}{2}$% Aquagel	46
004	2,3,6, 3/16" Pea	125	21	250	$6\frac{1}{2}$% Aquagel	48
005	2,3,4,6	120	12	180	($6\frac{1}{2}$% Aqua- (gel	50
006	2,3,4,6	120	21	70	(+ 6% Sand	56
007	Attempted test of lime affected Aquagel mud system was abandoned					
008	1,2,3,6	100-140	8-14	150	(0.9% old (stock (Hydro-	36
009	1,2,3,6	120	20	150	(pol	34
010	1,2,3,4	130	20	40	0.6% New Hydropol	45
011	1,2,3,4	100-130	12-28	120	0.6% New Hydropol + 6% Sand	52

V1 Test 001: Results and Observations

This test was run using a mud made from some old stock bentonite. It was made as a trial to test the equipment and procedure for recording results.

The mud was made up 6% by weight bentonite.

Mud was circulated for 3 hours prior to the start of the test and maintained at the following:-

Temperature = 20°C

Specific gravity = 1.04

Marsh funnel viscosity = 48 seconds

API Filter press ($\frac{1}{2}$ area) $7\frac{1}{2}$ minutes = 2.7 cc
30 " = 5.5 cc

Filter cake thickness = 1/32" to 2/32"

Mud was circulated at a velocity of 120 ft/min. past the face of the sample materials and a pressure differential of 20 psi was maintained.

The test was aborted after 10 minutes due to large mud losses through samples containing materials numbers 3 and 4.

No testing of samples after exposure was carried out.

Material 1

Porosity = 39.5%

(original) Linear K_o = 20 mm/min.

An effective seal formed immediately in the top 10 mm of the sample.

Material 2

Porosity = 43.5%

(original) Non-linear $K_o = 1/a = 120$ mm/min, $b/a^2 = .03$

Slowed up considerably after passing approximately 3 litres of filtrate. No investigation of the position of the seal was made.

Material 3

Porosity = 41.5%

(original) Non-linear K_o = 1/a = 730 mm/min, b/a^2 = .32

Material 4

Porosity = 44%

(original) Non-linear K_o = 1/a = 3900 mm/min, b/a^2 = 3.4.

Neither materials 3 or 4 looked like developing any seal against whole mud fluid loss. The large loss in mud from these two samples resulted in the water level in the bin dropping so low that air entered the pump thus causing the test to be abandoned after 10 minutes.

V2 Test 002: Results and Observations

Mud was made up as $6\frac{1}{2}\%$ by weight Aquagel.

Mud was circulated for 3 hours prior to starting the test and mud properties maintained as follows:-

Temperature = 22^{o}C

Specific gravity = 1.04

Marsh funnel viscosity = 48 seconds

API Filter Press ($\frac{1}{2}$ area) $7\frac{1}{2}$ minutes = 2 cc
30 " = 4.2 cc

Filter cake thickness = 1/32" to 2/32".

Mud was circulated at a velocity of 120 ft/min past the face of the sample materials and a pressure differential of 21 psi was maintained for the exposure duration of 5 hours.

After the 5 hours of exposure to the mud flow the test apparatus was isolated and all mud drained from above the samples. Water was then added and left standing 1 inch above the sample faces for 16 hours.

The samples were then removed, inspected and then retested for permeability to estimate the extent of damage caused by the mud.

Material 1

Porosity = 41%
(original) Linear K_o = 29 mm/min
(Table 2.1, Figures 2.1a, 2.5)

See Table 2.2. The volume of fluid passed from the sample was very quickly stemmed (1 minute) and the seal was above tapping 1. (64 mm from the exposed face). A steady but very slow loss of filtrate continued with time. The total collected filtrate volume of .235 litres indicates an estimated depth of mud filtrate penetration of 90mm.

When the sample was removed from the apparatus a distinct sealing layer was evident in the top 10 mm. The top 25 mm were removed from the sample and the material reinstalled and tested for permeability.

The overall sample permeability after extensive water flushing at pressures up to 25 psi was lower than the original unexposed material.

(exposed) K_e = 25 mm/min (Table 2.1, Figures 2.1b, 2.5)

An overall reduction in permeability of 15% has occurred.

Material 2

Porosity = 41.6%

(original) Non-linear $K_o = 1/a$ = 128 mm/min, b/a^2 = .023
(Table 2.1, Figures 2.2a, 2.5)

See Table 2.2. An effective seal was formed within ½ minute (somewhere in the top 64 mm of the sample) which prevented any further loss of mud filtrate beyond .19 litres. The total collected filtrate volume of .19 litres indicates an estimated depth of mud filtrate penetration of 70 mm.

When the sample was removed from the apparatus a distinct sealing layer was evident in the top 10 mm. The top 25 mm were removed, the sample reinstalled and the material retested for permeability. The results were as follows:-

(exposed) Non-linear $K_e = 1/a$ = 123 mm/min, b/a^2 = .023
(Table 2.1, Figures 2.2b, 2.5)

Only minor water flushing was carried out.

Negligible damage has been done to the material beyond the 10 mm in which the seal was formed.

Material 5

Porosity = 33.3%

The original material appears to be in two distinct layers.

(original) 0-216mm Linear K_o = 45 mm/min.
(original) 216-450 mm Linear K_o = 25 mm/min
(Table 2.1, Figures 2.3a, 2.5)

See Table 2.2. An effective seal was formed within ½ minute which prevented any further loss of mud filtrate beyond 0.1 litres. The total collected filtrate volume of 0.1 litres indicates an estimated depth of mud filtrate penetration of 50 mm.

When the sample was removed a distinct sealing layer was evident in the top 10 mm. This was as expected from the pressure tappings which indicated the seal to be somewhere in the top 64 mm. The top 25 mm were removed, the sample reinstalled and the material re-tested for permeability after minor flushing with water.

The results of these tests are now recorded:

(exposed) 25mm-114mm Linear K_e = 67 mm/min
114mm-216mm Linear K_e = 30 mm/min
216mm-450mm Linear K_e = 24 mm/min
(Table 2.1, Figures 2.3b, 2.5)

There has been no damage done to the material between 216-450 mm.

However, the layer between 0-216 mm has undergone change which needs interpretation. Between the developed seal (0-10mm) and 114 mm the results indicate an improvement in permeability from 45 to 67 mm/min. Between 114-216 mm the results indicate a loss of permeability from 45 to 30 mm/min. The removal of the top 25 mm from the sample was carried out with caution but with such a fine material it may be possible that the sample beyond the 25 mm was disturbed in such a way as to give the conflicting results. If tapping number 2 (114 mm) was blocked slightly it may have read high, thus indicating a change in permeability when one was not present.

The permeability based on readings from tappings 1 and 3 alone for the material between 25-216 mm was 40 mm/min. This indicates a reduction in permeability of 11%.

It is the author's opinion that negligible damage was done to the sample material beyond the 10 mm from the face in which the seal developed.

Material 6

Porosity = 35.5%

(original) Non-linear $K_o = 1/a$ = 170 mm/min, b/a^2 = .084
(Table 2.1, Figures 2.4a, 2.5)

See Table 2.2 and Figure 2.6. Whole mud flowed freely from the sample for the first two minutes. After two minutes an effective seal was formed and the loss of mud filtrate ceased. A total of 2.7 litres had been lost in the first 2 minutes. Tappings 1, 2 and 4 were blocked by mud and only the readings recorded in Table 2.2 were reliable.

The seal developed somewhere between tapping 5 and the end of the sample. Examination revealed that the seal had been initiated by the material retaining filter cloth, at the base of the sample.

If the filter had been coarser and had not caused the seal at the base of the sample material it is difficult to assess whether a seal would have formed elsewhere in the material.

When the sample was removed from the apparatus the seal was evident in the lower 20 mm of the material. The top 25 mm and the lower 25 mm were removed from the sample, the sample reinstalled and the material retested for permeability after extensive water flushing at pressures up to 25 psi.

The results were as follows:-

(exposed) 114-318 mm Non-linear $K_e = 1/a = 46$ mm/min, $b/a^2 = .13$
318-420 mm Non-linear $K_e = 1/a = 33$ mm/min, $b/a^2 = .12$
(Table 2.1, Figures 2.4a, 2.5)

Permanent damage has been done to the sample other than the area where the seal formed.

Reduction in permeability of 73-80% has occurred.

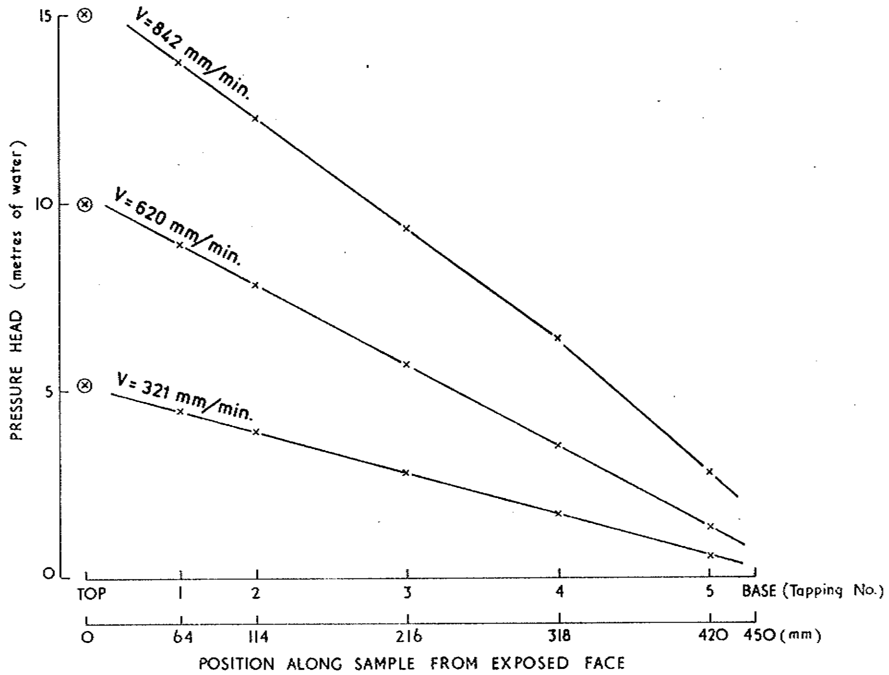


FIGURE 2·1(a) TEST 002. MATERIAL No. 1.

Pressure Distributions Before Exposure to Drilling Mud.

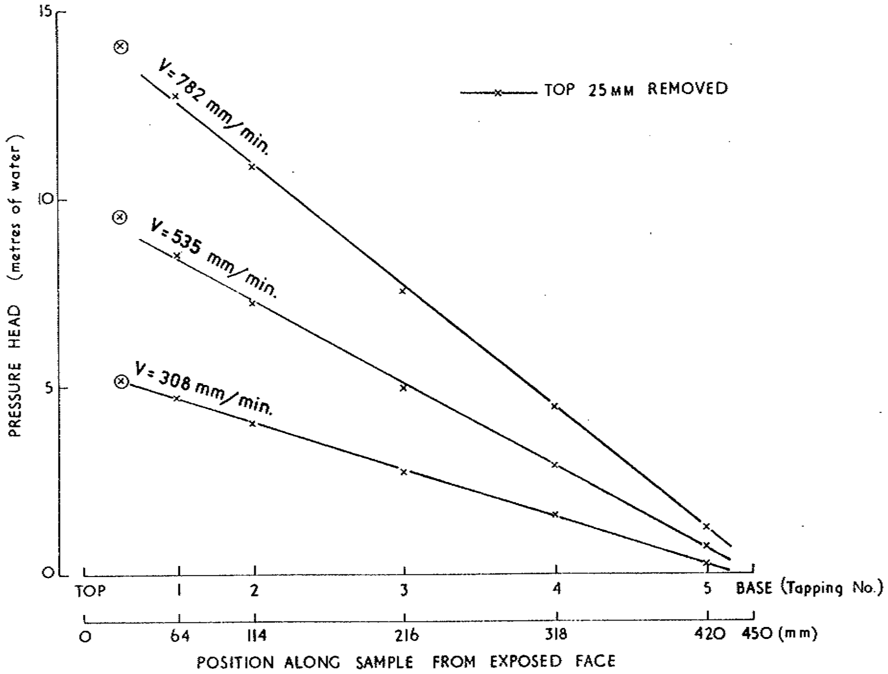


FIGURE 2·1(b) TEST 002. MATERIAL No. 1.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

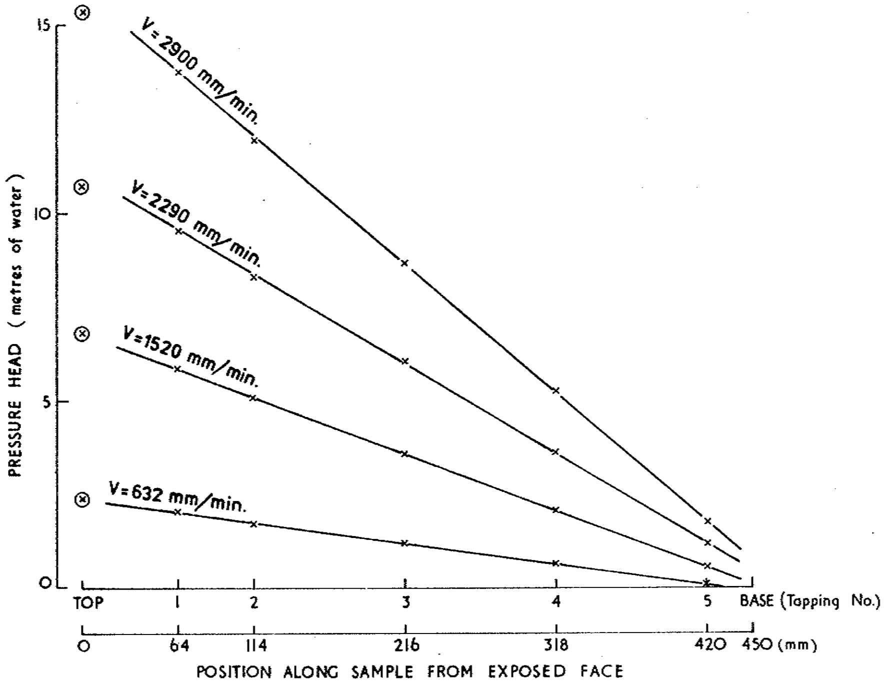


FIGURE 2·2(a) TEST 002. MATERIAL No. 2.
Pressure Distributions Before Exposure to Drilling Mud.

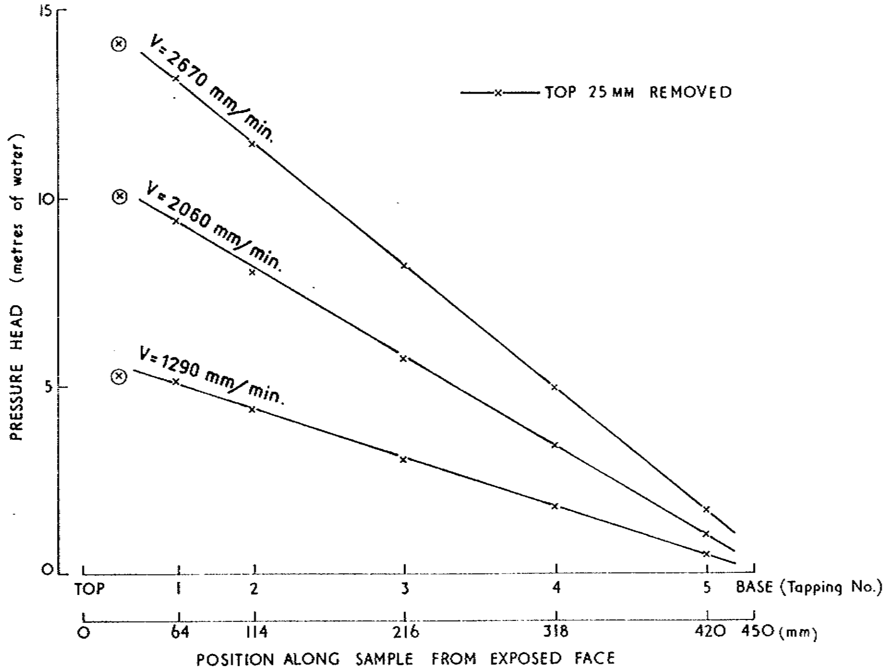


FIGURE 2·2(b) TEST 002. MATERIAL No. 2.
Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

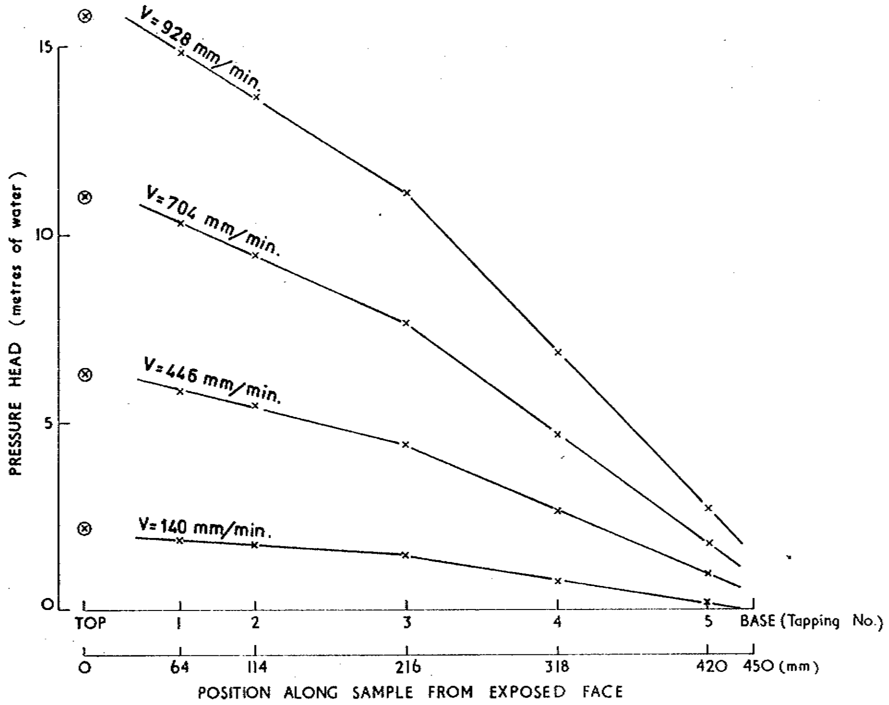


FIGURE 2·3(a) TEST 002. MATERIAL No. 5.
Pressure Distributions Before Exposure to Drilling Mud.

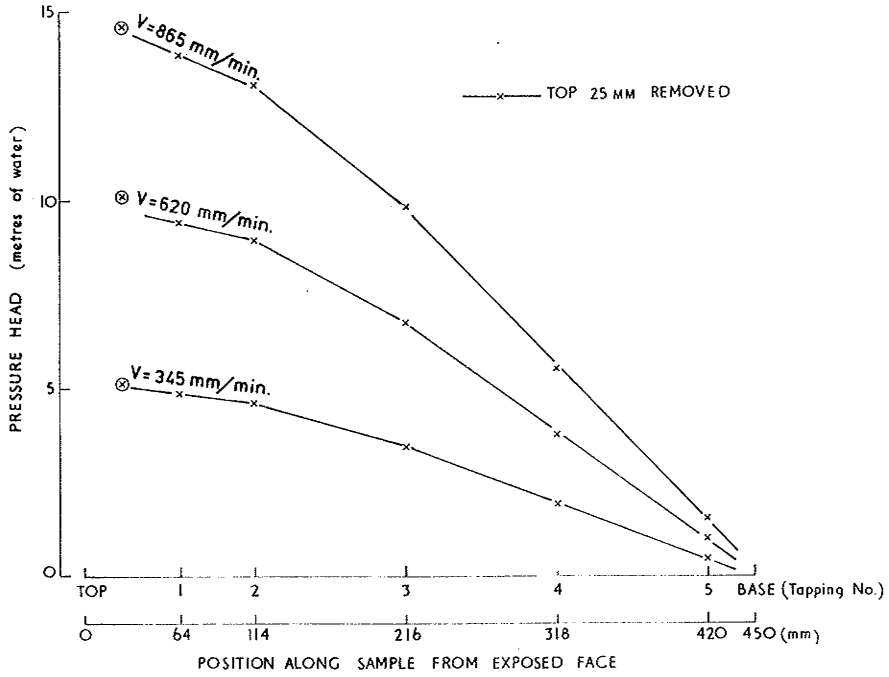


FIGURE 2·3(b) TEST 002. MATERIAL No. 5.
Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

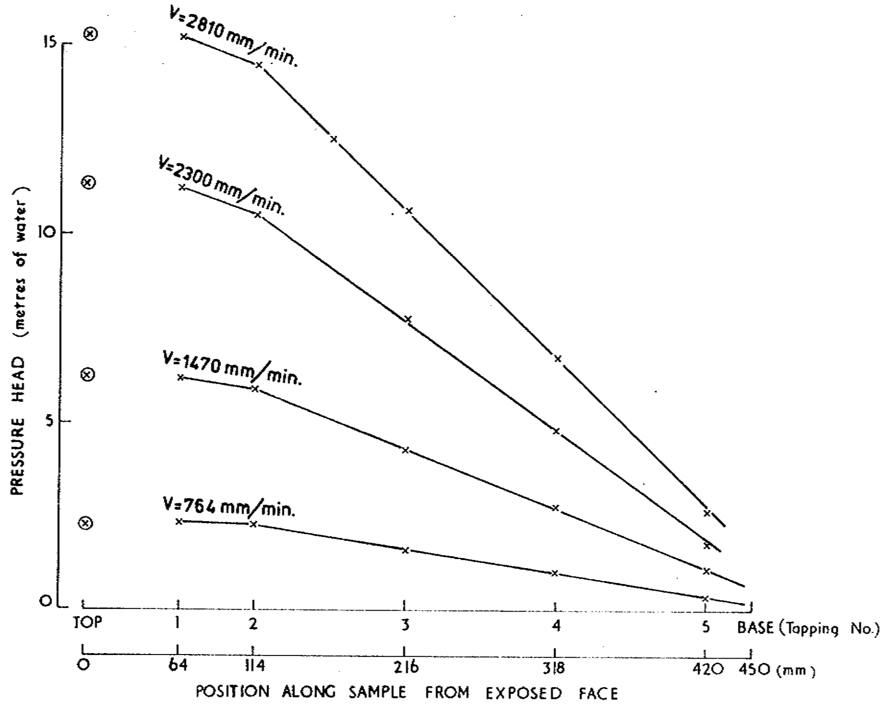


FIGURE 2·4(a) TEST 002. MATERIAL No. 6.

Pressure Distributions Before Exposure to Drilling Mud.

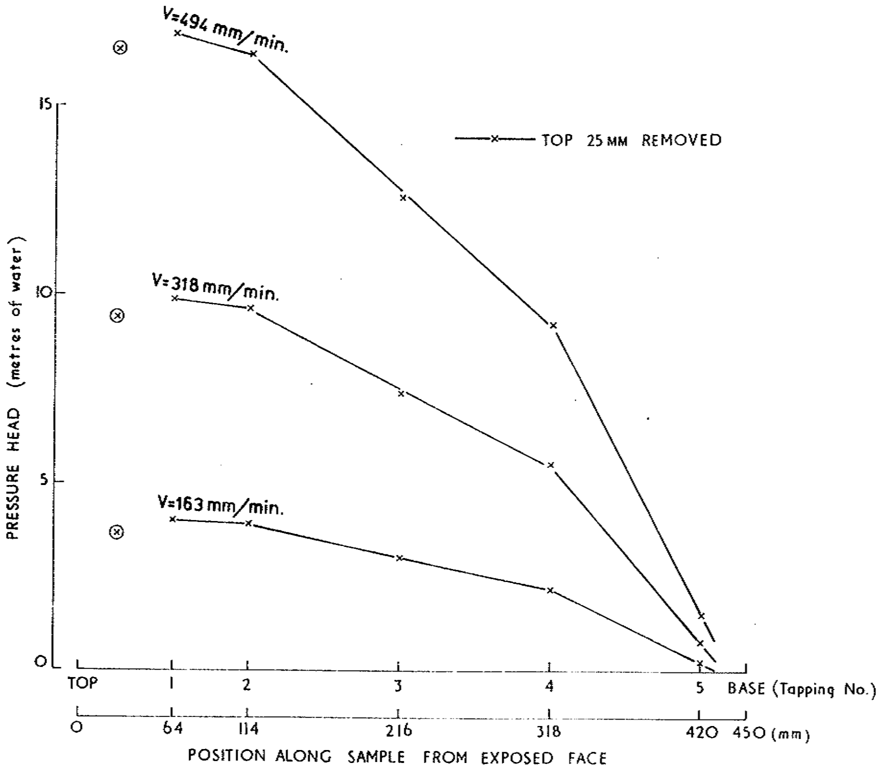
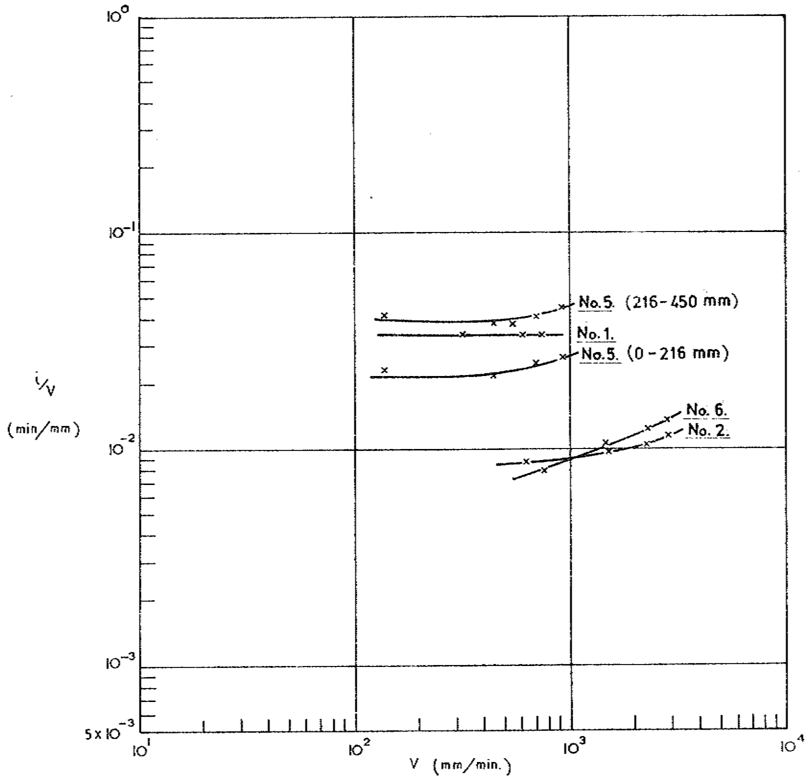
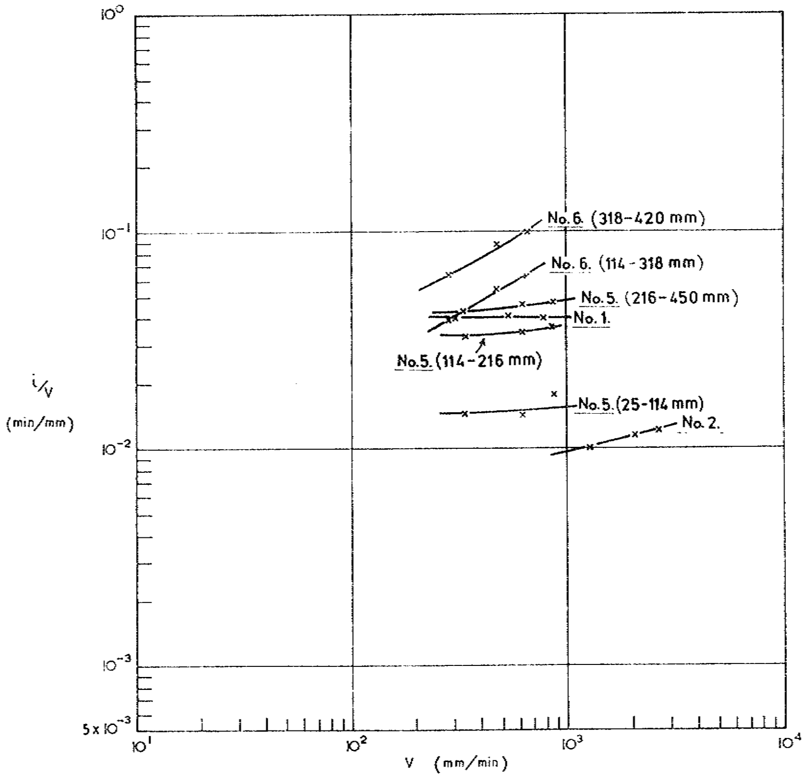


FIGURE 2·4(b) TEST 002. MATERIAL No. 6.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.



(a) Before Exposure to Drilling Mud



(b) After Exposure to Drilling Mud
Top 25 mm removed from sample

FIGURE 2·5 TEST 002

HYDRAULIC FLOW PROPERTIES OF TEST MATERIALS (i/V versus V)

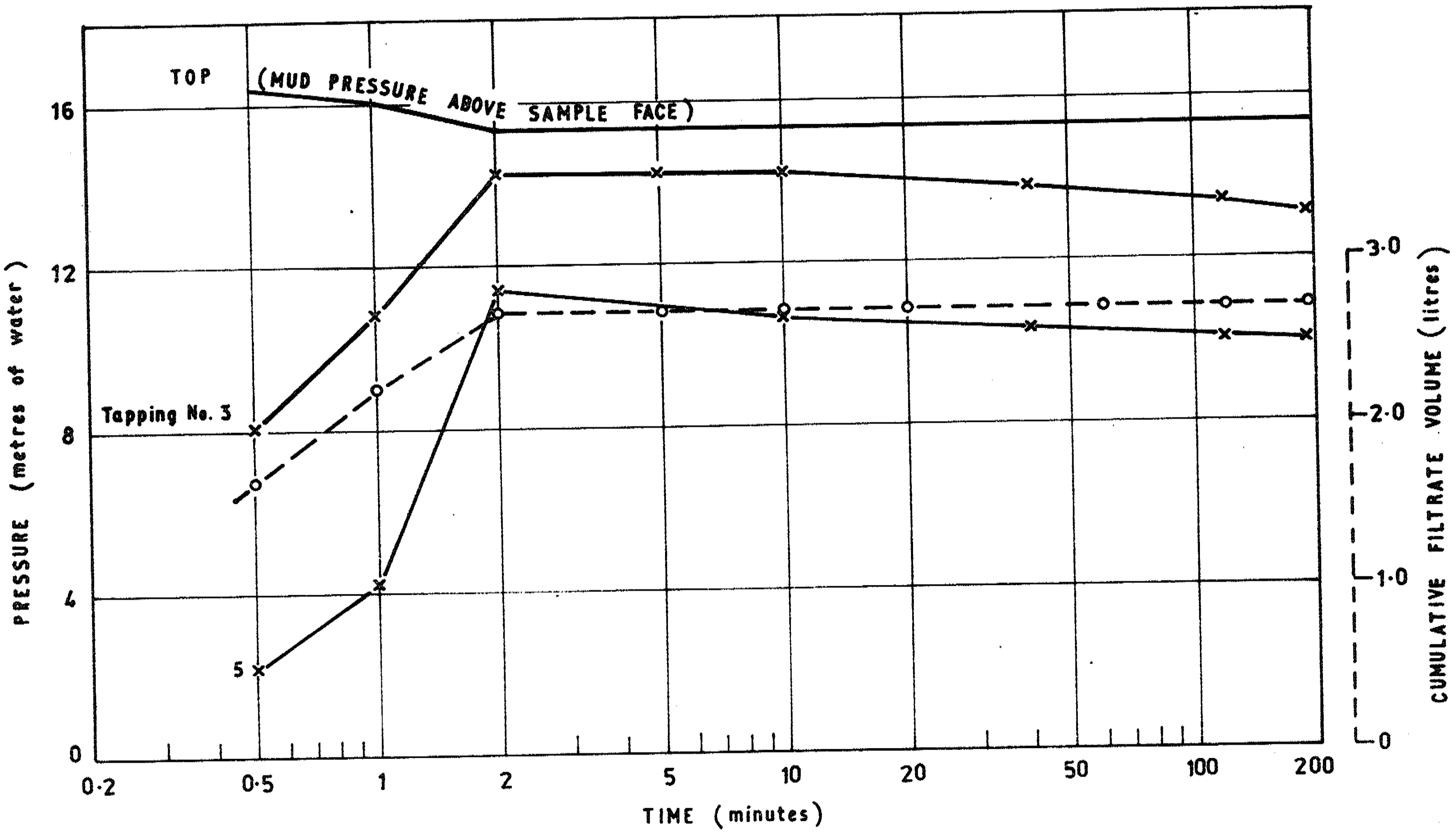


FIGURE 2·6: TEST 002 MATERIAL 6.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

TABLE: 2.1 **TEST:** 002

Permeability testing of material samples

Values of pressure (metres of water) as recorded at various positions along the sample for a measured flow of water through the sample.

Material	Flow Rate litres/min	Velocity mm/min	Tapping No.						
			Top		1	2	3	4	5
			Position along sample from datum (mm)						
			0	25	64	114	216	318	420
MATERIAL TESTS BEFORE EXPOSURE TO DRILLING MUD									
1	5.43	842	15.10		13.75	12.29	9.31	6.39	2.78
	4.00	620	9.95		8.89	7.82	5.69	3.59	1.33
	2.07	321	5.27		4.48	3.92	2.81	1.70	0.57
2	18.72	2900	15.32		13.75	11.91	8.68	5.27	1.77
	14.77	2290	10.56		9.54	8.29	6.03	3.62	1.15
	9.83	1520	6.78		5.86	5.06	3.59	2.08	0.57
	4.07	632	2.39		2.04	1.72	1.20	0.65	0.09
5	5.99	928	15.78		14.81	13.67	11.15	6.87	2.71
	4.54	704	11.01		10.32	9.45	7.65	4.65	1.77
	2.87	446	6.25		5.86	5.46	4.39	2.62	0.94
	0.91	140	2.17		1.84	1.73	1.43	0.78	0.22
6	18.12	2810	15.25		15.19	14.49	10.65	6.77	6.59
	14.84	2300	11.32		11.19	10.52	7.75	4.82	1.78
	9.48	1470	6.17		6.16	5.86	4.27	2.74	1.07
	4.93	764	2.24		2.33	2.26	1.62	1.00	0.37
MATERIAL TESTS AFTER EXPOSURE TO DRILLING MUD Top 25 mm removed from sample									
1	5.05	782		14.11	12.67	10.78	7.56	4.41	1.20
	3.45	535		9.57	8.47	7.19	4.98	2.84	0.70
	1.99	308		5.19	4.73	3.97	2.71	1.52	0.26
2	17.21	2670		14.11	13.17	11.34	8.19	4.92	1.64
	13.32	2060		9.95	9.39	8.07	5.74	3.41	1.07
	8.30	1290		5.26	5.17	4.41	3.03	1.77	0.51
5	5.58	865		14.79	13.80	13.04	9.83	5.48	1.52
	4.00	620		10.10	9.39	8.95	6.74	3.72	1.01
	2.23	345		5.19	4.85	4.60	3.47	1.89	0.44
6	3.19	494		16.45	16.82	16.32	12.54	9.20	1.45
	2.05	318		9.34	9.83	9.58	7.31	5.48	0.76
	1.05	163		3.60	3.97	3.85	2.96	2.16	0.24

TABLE: 2.2 **TEST:** 002

Sample behaviour during time of exposure to drilling mud.

Pressure (metres of water)

Material	Time (minutes)	Filtrate Volume (litres)	Tapping No. Top	1	2	3	4	5
			Position along sample from datum (mm) 0	64	114	216	318	420
1	½	0.19	16.40	.07	.07	.07	.07	.07
	1	.20	16.00	No change in any tapping levels throughout mud exposure.				
	2	.20	15.30					
	10	.20	15.30					
	40	.21	15.30					
	120	.22	15.30					
	190	.225	15.30					
	300	.235	14.80	.07	.07	.07	.07	.07
2	½	.19	16.40	.07	.07	.07	.07	.07
	1	.19	16.00	No change in any tapping levels throughout mud exposure				
	2	.19	15.30					
	190	.19	15.30	.07	.07	.07	.07	.07
5	½	.10	16.40	.07	.07	.07	.07	.07
	1	.10	16.00	No change in any tapping levels throughout mud exposure				
	2	.10	15.30					
	190	.10	15.30	.07	.07	.07	.07	.07
6	½	1.70	16.40			8.13	5.48	2.21
	1	2.26	16.00			10.78	7.37	4.22
	2	2.70	15.30			14.18		11.41
	10	2.70	15.30			14.15		10.71
	40	2.70	15.30			13.74		10.34
	120	2.70	15.30			13.30		10.02
	190	2.72	15.30			13.04		9.89
	300	2.73	14.80			12.79		9.77

V3 Test 003. Results and Observations

Mud was made up as $6\frac{1}{2}\%$ by weight Aquagel. Mud was circulated for 3 hours prior to starting the test and mud properties maintained as follows for the duration of the test.

Temperature = 22°C

Specific Gravity = 1.04

Marsh funnel viscosity = 46 seconds

API Filter Press ($\frac{1}{2}$ area) $7\frac{1}{2}$ minutes = 2 cc
30 minutes = 4 cc

Filter cake thickness = 1/32" to 2/32"

Mud was circulated at a velocity of 100 ft/min past the face of the sample materials and a pressure differential of 11 psi was maintained for the exposure duration of $3\frac{1}{4}$ hours.

After the 205 minutes of exposure to the mud flow, the test apparatus was isolated and all mud drained from above the samples. Water was then gently washed through the test cell for thirty minutes to clean all mud from the apparatus. Water was then added and left standing 3 inches deep above the sample material faces for 64 hours.

The permeability of the sample materials was then retested.

The samples were then removed, inspected, the top 25 mm removed from each material, reinstalled and retested for permeability to estimate the extent of damage caused by the mud.

Material 2

Porosity = 41%
(original) Non-linear K_o = $1/a$ = 129 mm/min, b/a^2 = .025
(Table 3.1, Figures 3.1a, 3.5)

See Table 3.2. An effective seal was formed within $\frac{1}{2}$ minute (somewhere in the top 64 mm of the sample) which prevented any further loss of mud filtrate beyond .56 litres. The total collected filtrate volume of 0.58 litres indicates an estimated depth of mud filtrate penetration of 220 mm.

After having been left standing with clean water above it for 64 hours, the seal was still effective in preventing any flow through the sample even under applied pressures of 15 psi.

When the sample was removed from the apparatus a distinct sealing layer was evident in the top 10 mm. The top 25 mm were removed and the sample reinstalled and the material retested for permeability after extensive flushing with water at pressures up to 20 psi.

The results were as follows:-

(exposed) 25-216 mm Non-linear $K_e = 1/a = 116$ mm/min, $b/a^2 = .039$
216-450 mm Non-linear $K_e = 1/a = 151$ mm/min, $b/a^2 = .035$
(Table 3.1, Figures 3.1b, 3.5)

Beyond the seal (0-10 mm) there appears to be a zone of permanently damaged material extending to a depth 216 mm from the exposed sample face. The material in this zone (25 - 216 mm) is more non-linear than the original material and has had its permeability reduced from $K_o = 129$ mm/min to $K_e = 116$ mm/min, i.e. it has undergone a reduction of 10% in permeability. The extent of this zone of reduced permeability (216 mm) coincides with the calculated depth of penetration of mud filtrate based on the total filtrate volume (220 mm).

Beyond 216 mm the sample material appears to be more permeable than the original sample. However, the material in this zone (216-450 mm) is also more non-linear than the original material. A permeability improvement of 17% appears to have occurred due to a change from $K_o = 129$ mm/min to $K_e = 151$ mm/min.

Alternatively, the percentage reduction and increase in permeability of the two zones may be estimated by comparing the necessary hydraulic gradient required to allow a specified velocity of flow. Proceeding in this manner using the data presented in Figure 3.5, the results are as follows:-

Specified Flow Velocity (mm/min)	Percentage Reduction in Permeability for Material 25-216 mm	Percentage Improvement in Permeability for Material 216-450mm
2000	-24%	+10%
1000	-20%	+15%

The exact magnitudes of the permeability variation are not of utmost importance. The important point is that there is a zone of damage (permeability reduction of the order of 20%) that is permanent and which extends to the limit of mud filtrate invasion at which point there is an abrupt increase in permeability to a value at least equal to that of the original sample.

The indicated improvement in permeability beyond a depth of 216 mm is difficult to interpret. It may be due to flushing of the material fines from the lower portion of the sample during the extended time in which flow has occurred through the sample since the original permeability testing. An alternative but less likely interpretation may be the occurrence of errors in recording experimental results.

Material 6

Porosity = 33%
(original) Non-linear K_o = $1/a$ = 91 mm/min, b/a^2 = 0.05
(Table 3.1, Figures 3.2a, 3.5)

See Table 3.2 and Figure 3.6. An effective seal developed (at some position between tappings 1 and 2 i.e. between 64 and 114 mm) after 5 minutes which prevented any further loss of mud filtrate beyond 1.3 litres. The total collected filtrate volume of 1.31 litres indicated that mud filtrate has passed through the entire sample length (estimated depth of penetration is 620 mm).

The sample was left covered with clear water for 64 hours. After this time the seal was effective in preventing any flow through the material even under applied pressures of 15 psi.

When the sample was removed from the apparatus the following visual inspection revealed -

(a) no significant layer at the sample top,

(b) mud was evident throughout the entire sample length,

(c) the mud appears to be thicker in the top 160 mm of the sample.

The top 25 mm were removed and the sample reinstalled and the material retested for permeability after extensive water flushing at pressures up to 25 psi.

The results were as follows:-

(exposed) 64-114 mm Non-linear K_e = $1/a$ = 15 mm/min, b/a^2=.035
114-216 mm Non-linear K_e= $1/a$ = 15 mm/min, b/a^2=.018
216-318 mm Non-linear K_e= $1/a$ = 27 mm/min, b/a^2=.046
318-450 mm Non-linear K_e = $1/a$ = 157 mm/min, b/a^2 = .77
(Table 3.1, Figures 3.2b, 3.5)

The material appears to have suffered a permanent reduction in permeability of 84% (K_o = 91 to K_e = 15 mm/min) in the upper 216 mm of the sample. This includes the zone between tappings 1 and 2 (64-114 mm) in which the seal occurred. The material in this zone is slightly more linear than the original sample.

There is a minor improvement in permeability between 216 and 318 mm where the reduction in permeability is 70% (K_o = 91 to K_e = 27 mm/min) and the material is essentially of equal non-linearity to the original.

Beyond 318 mm the sample shows a marked apparent improvement in permeability of 70% which is difficult to interpret (K_o = 91 to K_e = 157 mm/min).

However, the flow characteristics of this apparently improved zone are far more non-linear than those of the original (b/a^2 increases from 0.05 in the original to 0.77 in this zone) and any comparison with the original material should be made with caution. The percentage reductions and increases in permeability over the sample length may also be estimated by comparing the necessary hydraulic gradients required to allow a specified velocity of flow. The results of such a procedure using the data of Figure 3.5 are now presented.

Specified Flow Velocity mm/min	Percentage change in permeability from the original			
	64-114mm	114-216mm	216-318mm	318-450mm
500	-90%	-85%	-80%	-34%
300	-88%	-85%	-77%	-19%

The resultant description of the permanent damage caused by exposure to the mud may now be stated.

The material has suffered a permanent reduction in permeability of 85-90% to a depth of 216 mm. This zone includes the region in which the seal against further mud filtrate losses was developed (64-114 mm). A slight improvement occurs between 216 and 318 mm where the percentage reduction in permeability is 80%.

At 318 mm from the exposed face there is a dramatic improvement in permeability. Beyond 318 mm the permeability is at least equal to that of the original sample although long term flushing of the sample may have lead to the dramatic increase in the non-linearity of the material in this zone.

As can be seen the damage appears to follow a step function, changing abruptly from a zone of permanent damage to a comparatively undamaged zone at a depth of 310 mm from the exposed sample face.

Material 3

Porosity = 40%

V3.5

(original) Non-linear $K_o = 1/a = 563$ mm/min, $b/a^2 = .24$
(Table 3.1, Figures 3.3a, 3.5)

See Table 3.2 and Figure 3.7. An effective seal formed gradually over 10 minutes which prevented any further loss of mud filtrate beyong 15 litres. The seal appears to be above tapping 1 and thus somewhere between 0 and 64 mm. Whole mud solids were passed through the entire sample in the early stages of this test prior to the formation of the seal.

The sample was left covered with clear water for 64 hours. After this time the seal was effective in preventing any flow through the material even under pressures of 15 psi.

When the sample was removed from the apparatus the following visual inspection revealed -

(a) no distinct sealing layer in the top 10 mm of the sample although a definite reduction in permeability was visually evident;

(b) whole mud was evident in patches throughout the entire sample length.

The top 25 mm were removed and the sample reinstalled and the material retested for permeability after flushing with water at pressures up to 20 psi. The flushing was carried out until no further improvement was possible with further water flow. The material cleared up very quickly and only a small degree of flushing with clear water was required.

The results on the cleaned up material were as follows:

(exposed) 25-216 mm Non-linear $K_e = 1/a = 440$ mm/min, $b/a^2 = .26$
216-450 mm Non-linear $K_e = 1/a = 700$ mm/min, $b/a^2 = .54$
(Table 3.1, Figures 3.3b, 3.5)

For materials with $b/a^2 > 0.1$ the reliability of extrapolating non-linear equations ($i = aV + bV^2$) as determined from only 3 points to a value of permeability $K = 1/a$ is very low. In such cases, comparisons of permeability and subsequent estimates of damage may be more reliably evaluated by comparing the hydraulic gradients necessary to achieve specified flow velocities. This was done for several velocities and the results were as follows:-

Specified Flow Velocity mm/min	Percentage change in permeability from the original	
	25-216 mm	216 - 450 mm
4000	-39%	-18%
3000	-37%	-13%
2000	-34%	-8%

The material has suffered a permanent reduction in permeability of the order of 35% to a depth of 216 mm. At 216 mm from the exposed face there is an abrupt change. Beyond 216 mm the material has suffered permanent damage, resulting in a reduction in permeability of the order of 10%.

Material 4

Porosity = 41%

(original) Non-linear $K_o = 1/a = 2900$ mm/min, $b/a^2 = 2$
(Table 3.1, Figures 3.4a, 3.5)

See Table 3.2. The mud flow from material 4 was large and did not look as if a seal would form. The sample was isolated after 2 minutes. The valve in the line below the sample was closed due to difficulties encountered in handling the large volumes of mud being collected and returned to the main mud storage bin.

The sample was left covered with clear water for 64 hours after the mud flow ceased. When retested for permeability the mud sitting within the sample was quickly flushed out and the material appeared to have suffered little damage although no measurements were recorded at this stage.

The sample was removed from the apparatus and the top 25 mm removed. There was no visual evidence of any mud within the material. The sample was reinstalled and the material retested for permeability after a minor amount of extra flushing with water.

The results were as follows:-

(exposed) Non-linear $K_e = 1/a = 1900$ mm/min $b/a^2 = 0.6$
(Table 3.1, Figures 3.4b, 3.5)

For materials with $b/a^2 > 0.1$ the reliability of extrapolating non-linear equations ($i = aV + bV^2$) as determined from only 3 points to a value of permeability $K = 1/a$ is very low. In such cases estimates of damage may be more reliably evaluated by comparing the hydraulic gradients necessary to achieve specified flow velocities. This was done for two velocities (in the range over which permeability testing was carried out) and the results were as follows:-

Specified Flow Velocity mm/min	Percentage Variation in Permeability from the original material
4000	+4%
7000	+17%

Material 4 passed whole mud without affecting a seal. However, mud was easily removed from the material and full recovery of original permeability was easily achieved by minimal flushing with water.

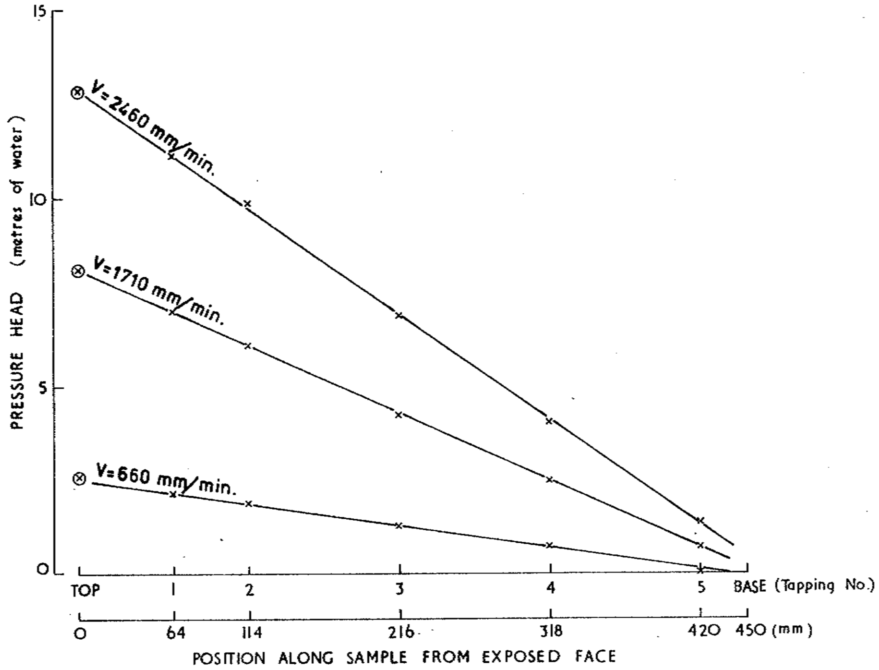


FIGURE 3·1(a) TEST 003. MATERIAL No. 2.
Pressure Distributions Before Exposure to Drilling Mud.

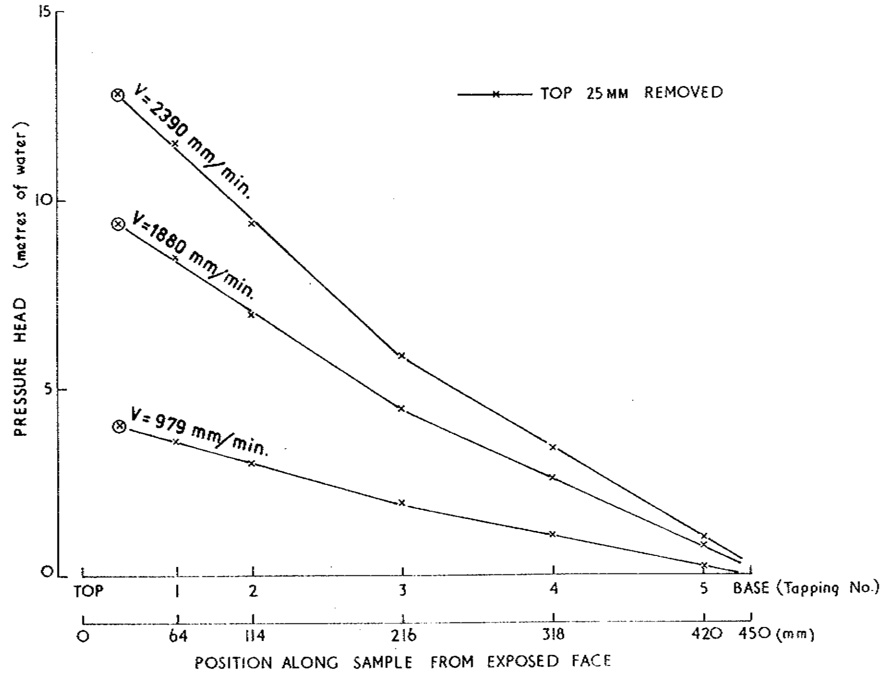


FIGURE 3·1(b) TEST 003. MATERIAL No. 2.
Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

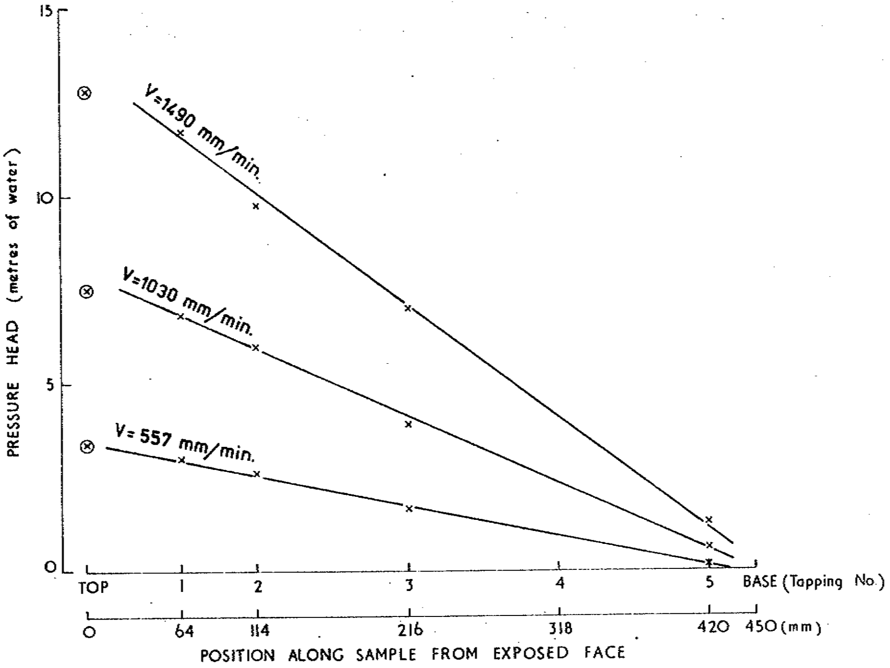


FIGURE 3·2(a) TEST 003. MATERIAL No. 6.

Pressure Distributions Before Exposure to Drilling Mud.

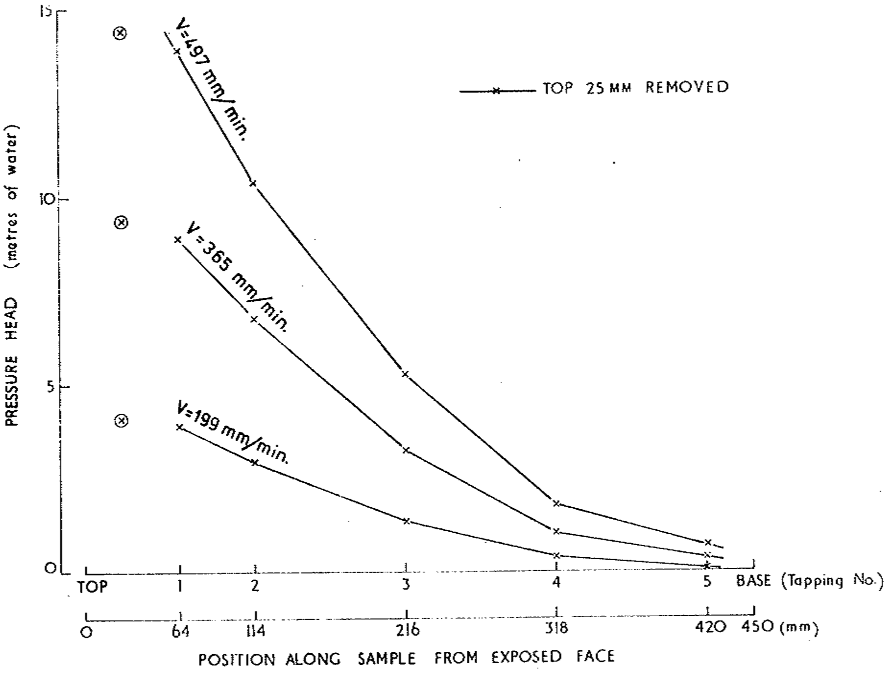


FIGURE 3·2(b) TEST 003. MATERIAL No. 6.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

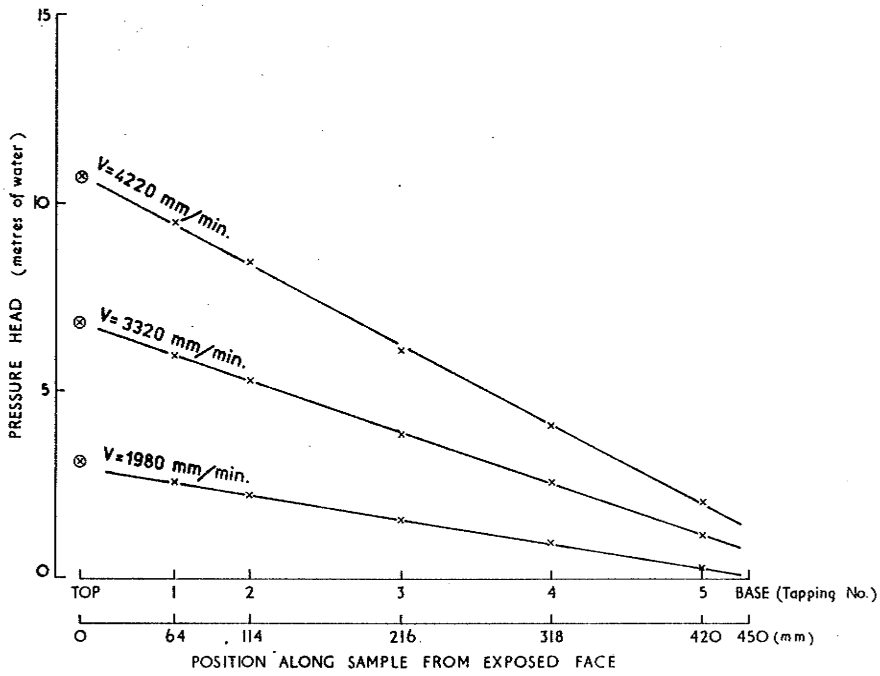


FIGURE 3·3(a) TEST 003. MATERIAL No. 3.
Pressure Distributions Before Exposure to Drilling Mud.

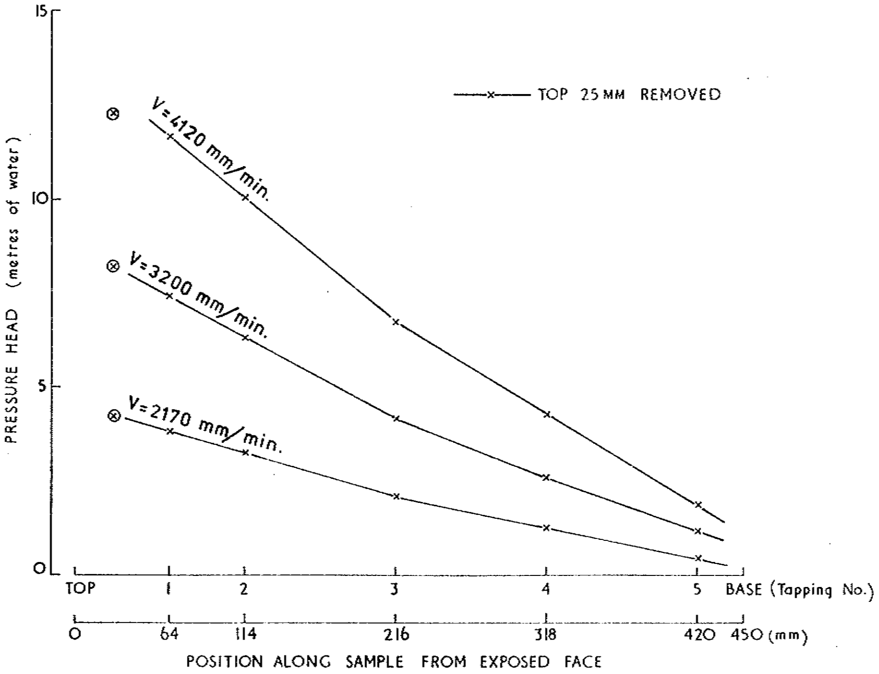


FIGURE 3·3(b) TEST 003. MATERIAL No. 3.
Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

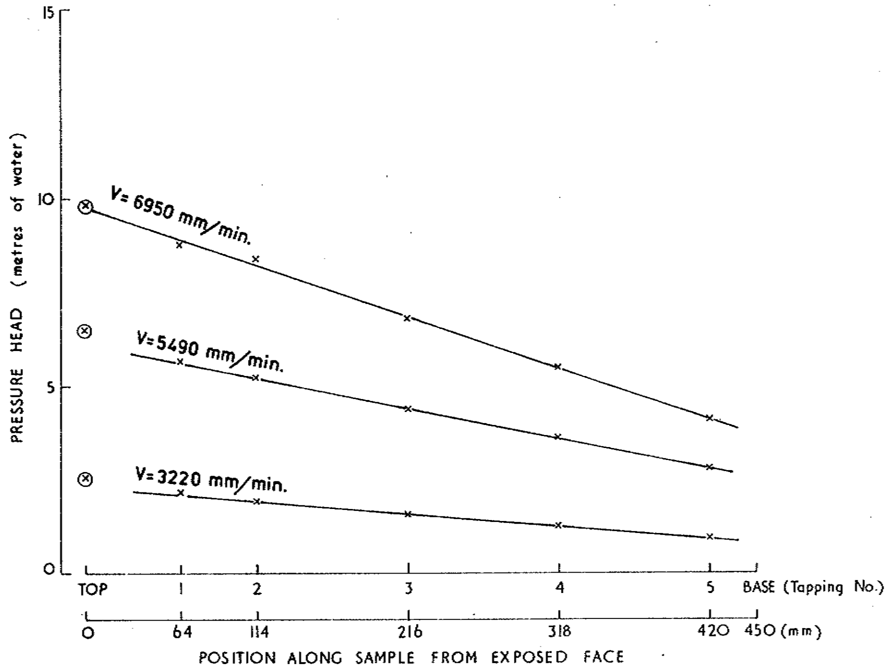


FIGURE 3·4(a) TEST 003. MATERIAL No. 4.

Pressure Distributions Before Exposure to Drilling Mud.

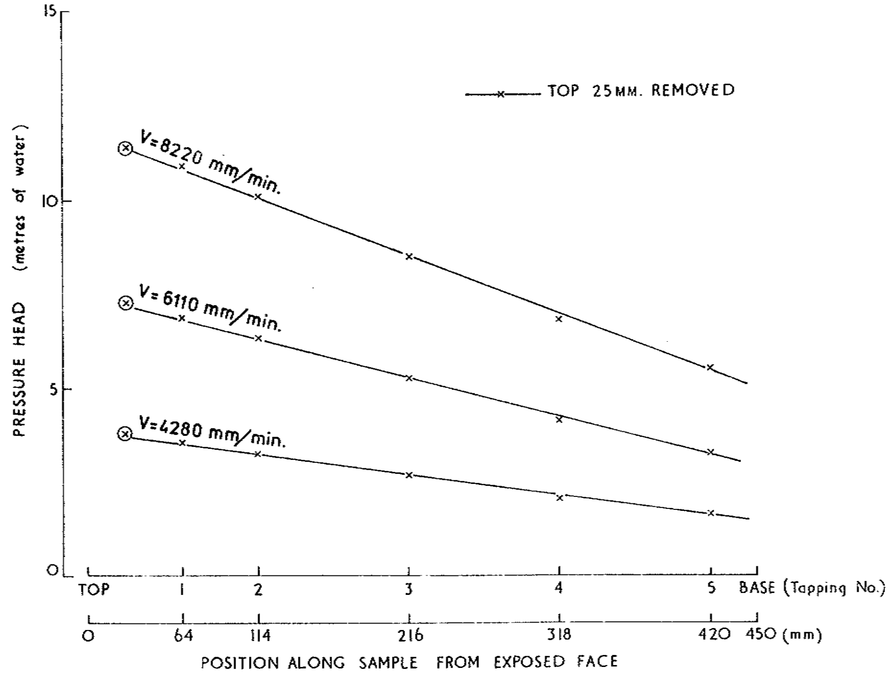
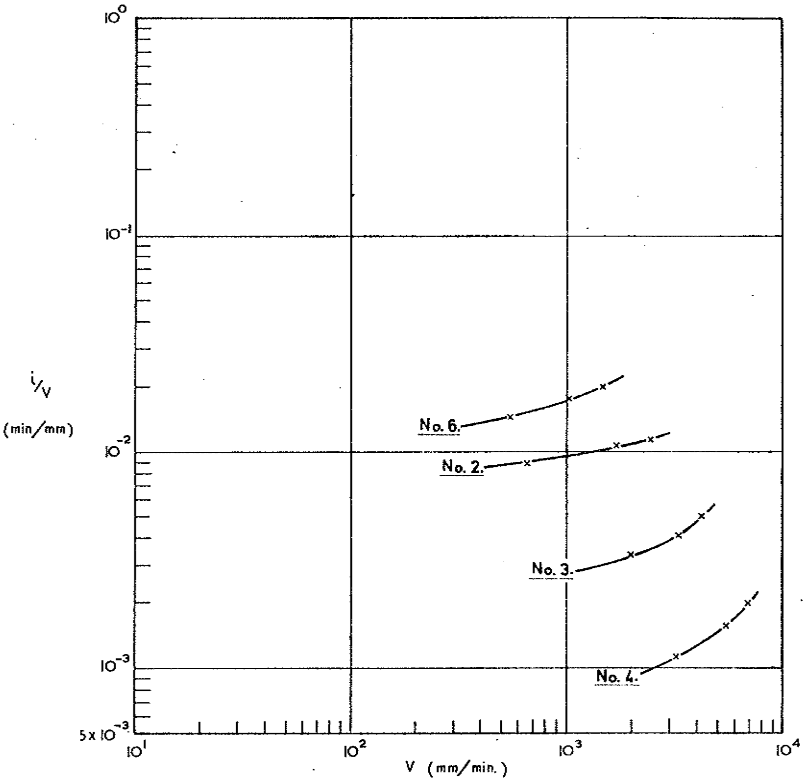
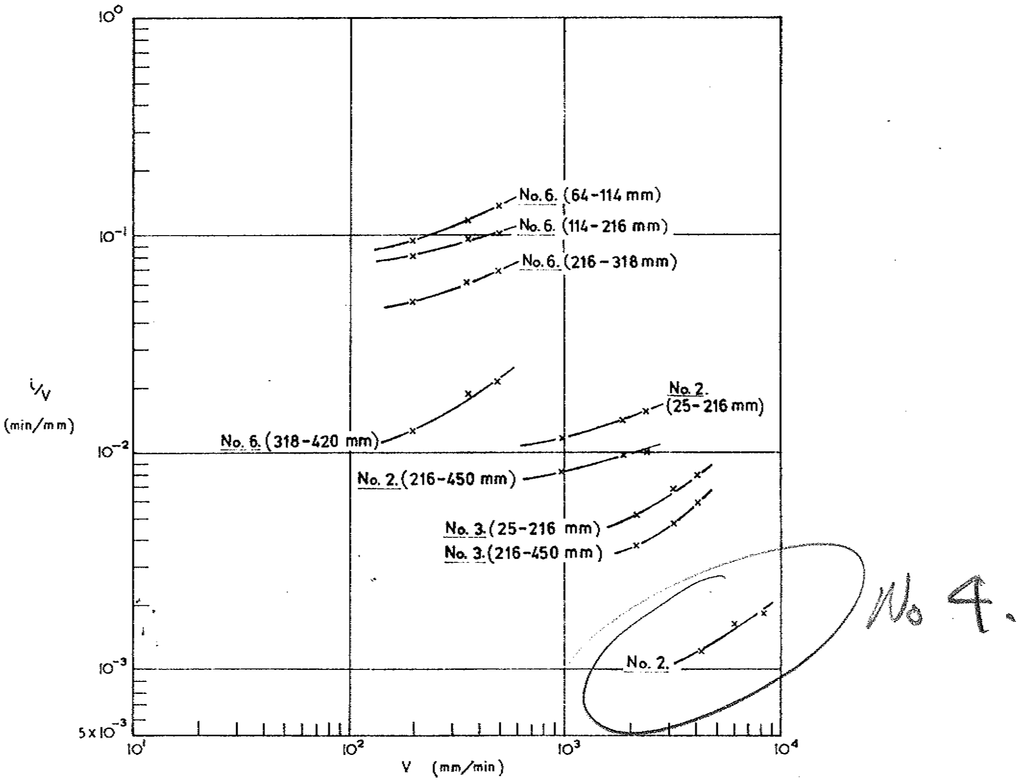


FIGURE 3·4(b) TEST 003. MATERIAL No. 4.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.



(a) Before Exposure to Drilling Mud



(b) After Exposure to Drilling Mud
Top 25mm removed from sample

FIGURE 3·5 . TEST 003

HYDRAULIC FLOW PROPERTIES OF TEST MATERIALS (i/V versus V)

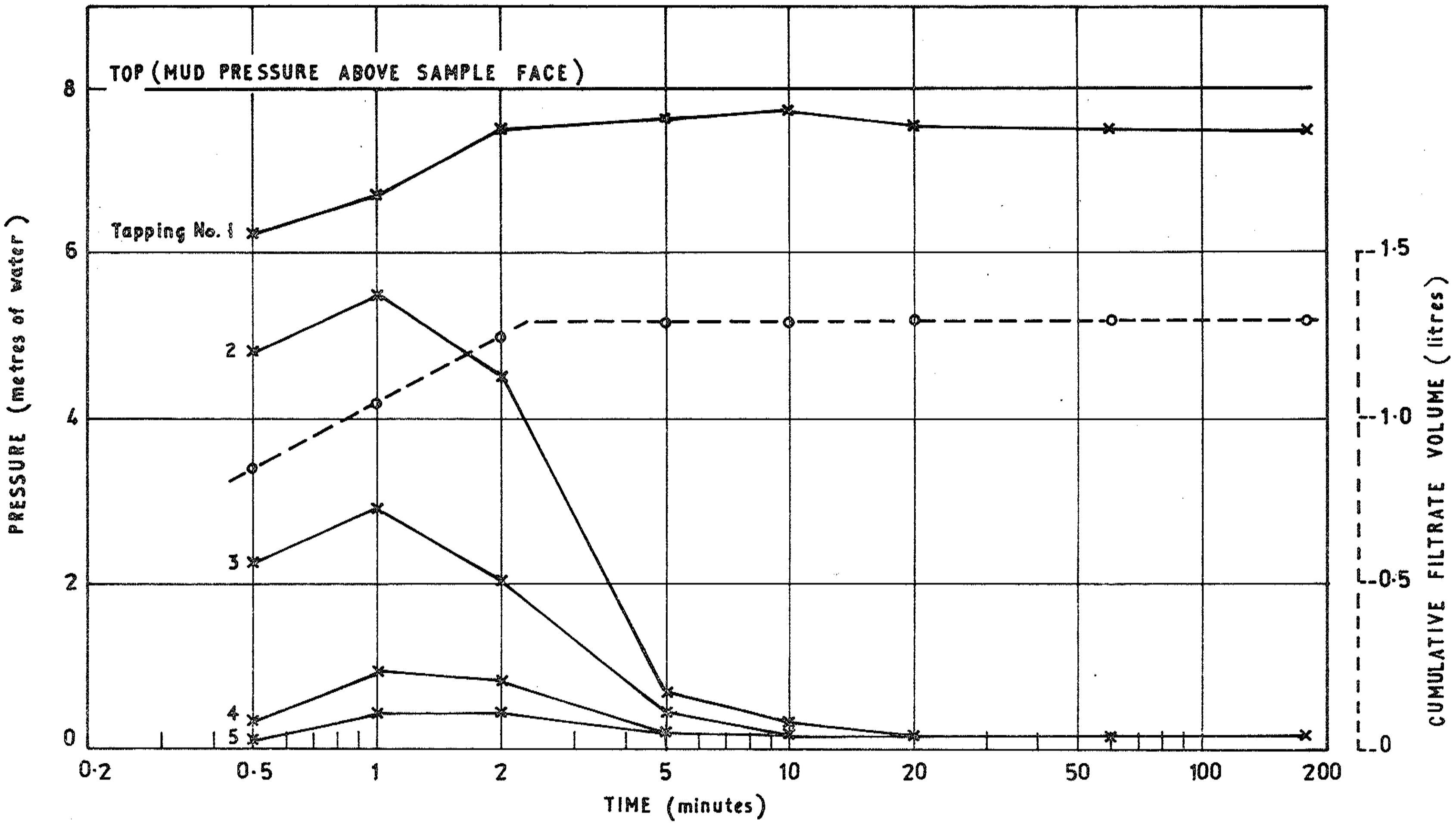


FIGURE 3-6: TEST 003 MATERIAL 6.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

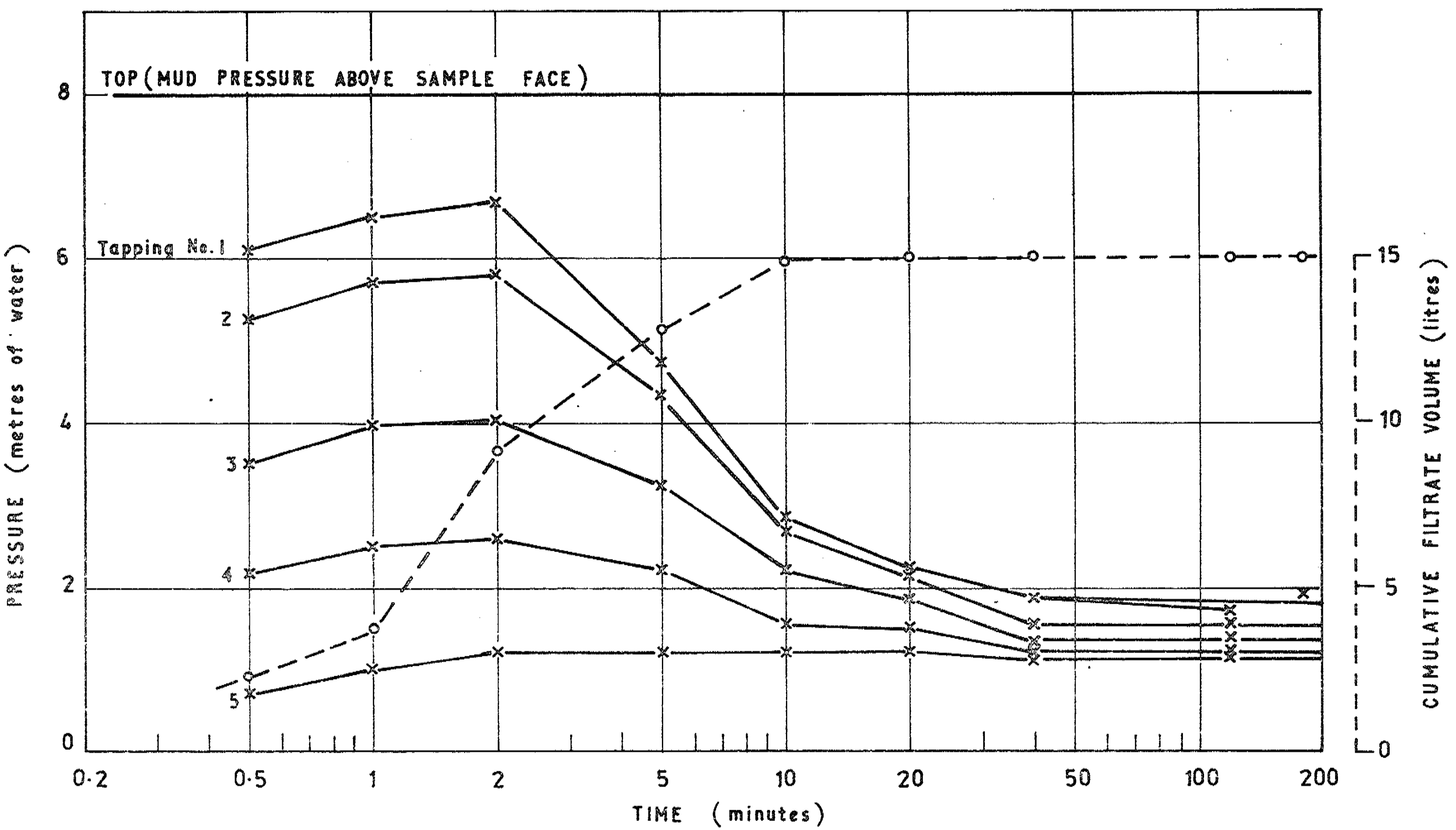


FIGURE 3·7: TEST 003 MATERIAL 3.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

<u>TABLE</u>: 3.1 <u>TEST</u>: 003

Permeability testing of material samples

Values of pressure (metres of water) as recorded at various positions along the sample for a measured flow of water through the sample.

Material	Flow Rate litres/min	Velocity mm/min	Tapping No.						
			Top		1	2	3	4	5
			Position along sample from datum (mm)						
			0	25	64	114	216	318	420
MATERIAL TESTS BEFORE EXPOSURE TO DRILLING MUD									
2	15.88	2460	12.90		11.15	9.89	6.87	4.04	1.33
	11.05	1710	8.15		7.00	6.11	4.22	2.46	0.70
	4.27	660	2.62		2.15	1.89	1.27	0.70	0.07
6	9.63	1490	12.75		11.72	9.77	7.00		1.33
	6.65	1030	7.45		6.87	5.99	3.91		0.70
	3.59	557	3.30		2.96	2.62	1.64		0.19
3	27.2	4220	10.70		9.52	8.45	6.11	4.10	2.08
	21.4	3320	6.85		5.99	5.30	3.85	2.59	1.20
	12.8	1980	3.07		2.59	2.21	1.58	0.95	0.32
4	44.8	6950	9.87		8.76	8.38	6.74	5.48	4.04
	35.4	5490	6.47		5.61	5.17	4.35	3.59	2.71
	20.8	3220	2.62		2.12	1.89	1.52	1.20	0.89
MATERIAL TESTS AFTER EXPOSURE TO DRILLING MUD Top 25 mm of Sample Removed									
2	15.43	2390		12.82	11.47	9.33	5.86	3.34	0.95
	12.11	1880		9.34	8.45	6.93	4.41	2.52	0.76
	6.32	979		3.98	3.59	2.96	1.83	1.01	0.19
6	3.21	497		14.41	13.86	10.34	5.23	1.77	0.70
	2.35	365		9.27	8.89	6.74	3.22	1.01	0.32
	1.29	199		4.05	3.91	2.96	1.36	0.38	0.13
3	26.55	4120		12.14	11.66	10.02	6.74	4.22	1.89
	20.66	3200		8.14	7.44	6.30	4.16	2.59	1.14
	14.00	2170		4.13	3.78	3.22	2.08	1.26	0.44
4	53.00	8220		11.46	10.84	10.02	8.45	6.81	5.55
	39.4	6110		7.30	6.87	6.30	5.23	4.10	3.28
	27.6	4280		3.83	3.53	3.22	2.65	2.02	1.64

TABLE: 3.2 **TEST:** 003

Sample behaviour during time of exposure to drilling mud.

Pressure (metres of water)

Material	Time (minutes)	Filtrate Volume (litres)	Tapping No.					
			Top	1	2	3	4	5
			Position along sample from datum (mm)					
			0	64	114	216	318	420
2	½	.56	7.98	.32	.26	.19	.13	.13
	1	.56	7.98	.51	.26	.19	.13	.13
	2	.56	7.98	.44	.26	.19	.19	.13
	5	.56	7.98	.26	.26	.19	.19	.13
	10	.56	7.98	.19	.19	.19	.19	.19
	60	.56	7.98	.19	.19	.19	.19	.19
	180	.58	7.98	.19	.19	.19	.19	.19
6	½	.85	7.98	7.25	4.79	2.23	.32	.13
	1	1.05	7.98	6.68	5.48	2.90	.95	.44
	2	1.25	7.98	7.50	4.48	2.02	.82	.44
	5	1.30	7.98	7.63	.70	.44	.19	.19
	10	1.30	7.98	7.75	.32	.19	.19	.19
	20	1.30	7.98	7.56	.19	.19	.19	.19
	60	1.30	7.98	7.50	.19	.19	.19	.19
	180	1.31	7.98	7.50	.19	.19	.19	.19
3	½	2.3	7.98	6.11	5.23	3.53	2.15	.70
	1	3.7	7.98	6.49	5.74	3.97	2.46	1.01
	2	9.1	7.98	6.68	5.80	4.04	2.59	1.20
	5	12.8	7.98	4.73	4.29	3.22	2.21	1.20
	10	14.9	7.98	2.84	2.65	2.15	2.21	1.20
	20	15.0	7.98	2.21	2.18	1.83	1.52	1.20
	40	15.0	7.98	1.83	1.58	1.33	1.20	1.14
	120	15.0	7.98	1.70	1.58	1.36	1.23	1.14
	180	15.0	7.98	1.95	1.77	1.51	1.26	1.14
4	½	7.6	7.98	6.24	5.61	4.48	3.34	2.15
	1		7.98	6.62	5.99	4.98	3.72	2.46
Did not look at all like sealing - sample isolated after 2 minutes.								

V4 Test 004. Results and Observations

Mud was made up as $6\frac{1}{2}\%$ by weight Aquagel. Mud was circulated for 3 hours prior to starting the test and mud properties maintained as follows for the duration of the test.

Temperature = $21^{\circ}C$

Specific gravity = 1.04

Marsh funnel viscosity = 48 seconds

API Filter press ($\frac{1}{2}$ area) $7\frac{1}{2}$ minutes = 2 cc
30 minutes = 4 cc

Filter cake thickness = 1/32" to 2/32"

Mud was circulated at a velocity of 125 ft/min. past the face of the sample materials and a pressure differential of approximately 21 psi was maintained for the exposure duration of 4 hours 10 minutes.

After the 250 minutes of exposure to the mud flow the test apparatus was isolated and all mud drained from above the samples. Water was then washed through the test cell for thirty minutes to clean all mud from the apparatus. Water was then added and left standing 3 inches deep above the sample material faces for 68 hours.

The permeability of the sample materials was then retested in their present condition.

The samples were then removed, inspected, the top 25 mm removed from each material, reinstalled and retested for permeability to estimate the extent of damage caused by the mud.

Finally the samples were removed and in two cases where marked layering of the sample material was evident closer inspection of the individual layers was made.

Material 2

Porosity = 40%

(original) Non-linear $K_o = 1/a = 154$ mm/min, $b/a^2 = .033$
(Table 4.1, Figures 4.16, 4.5)

See Table 4.2. An effective seal was formed within $\frac{1}{2}$ minute (somewhere in the top 64 mm of the sample) which prevented any further loss of mud filtrate beyond .92 litres. The total collected filtrate volume of .94 litres indicates an estimated depth of mud filtrate penetration of 365 mm.

The mud was drained from the apparatus and then water was flushed through the test cell to remove all mud from the apparatus. Water was then left standing 3 inches deep above the sample face for 68 hours prior to retesting the material permeability.

Under a pressure of 20 psi water initially flowed slowly from the sample but in a very short time the flow increased and indicated an almost complete return to original permeability. The material was flushed through for approximately 15 minutes and permeability tests carried out (see Table 4.1 and Figure 4.1b).

The sample was removed from the apparatus and inspected. Remains of a distinct sealing layer in the top 10 mm of the sample were evident in patches over the cross sectional area of the top of the sample. It is the author's opinion that the 10 mm sealing layer was broken up by the water washing of the test cell which was carried out immediately after the cessation of mud flow. In the previous test 003 the same procedure was applied but the sealing layer remained intact and prevented any flow of clean water even under pressures of 15 psi. The washing was more gently carried out in Test 003.

The top 25 mm were removed from the sample which was then reinstalled and retested for permeability. Minor water flushing was carried out.

The results of such tests were as follows:-

(exposed) Non-linear $K_e = 1/a$ = 149 mm/min, b/a^2 = 0.042
(Table 4.1, Figures 4.1b, 4.5)

With the available accuracy there appears to be no permanent damage to the material beyond the sealing layer which developed in the top 10 mm of the sample.

Material 6

Porosity = 32%

(original) 0-216 mm Non-linear K_o = 1/a = 310 mm/min, b/a^2 = .280
216-318 mm Non-linear K_o=1/a = 40 mm/min, b/a^2 = .009
318-450 mm Non-linear K_o=1/a =108 mm/min, b/a^2 = .06
(Table 4.1, Figures 4.2a, 4.5)

As can be seen the material has various layers of differing permeability throughout its length. Probably the variation is due to non-uniform porosity of the sample.

See Table 4.2 and Figure 4.6. An effective seal formed within two minutes which prevented any further loss of mud filtrate beyond 1.35 litres. The seal has formed somewhere between tappings 3 and 4. This corresponds to the position of the least permeable layer (K_o = 40 mm/min) between 216 and 318 mm from the exposed face. The total collected filtrate volume of 1.39 litres indicates that mud filtrate had penetrated the entire sample length (estimated penetration = 675 mm).

After draining and washing of the mud from the test apparatus the sample was left under water for 68 hours. Then attempts were made to flush water through the sample. Under pressures up to 25 psi not much more than a trickle could be forced through the sample. Two permeability tests were carried out at these low flow velocities and are recorded in Table 4.1 and Figure 4.2b.

The sample was removed from the apparatus and inspected. There was a noticeable layer of reduced permeability in the top 10mm of the sample, but it was not distinct. The effective sealing layer was clearly visible between tappings 3 and 4 (216-318 mm). In fact, the seal was visually apparent and was recorded as being a definite 20 mm thick layer between 280 and 300 mm from the sample top.

The top 25 mm were removed from the sample which was reinstalled and then the material was retested for permeability. Extensive attempts to water flush the sample clean and improve the flow through the sample proved fruitless. Pressures up to 25 psi were applied with virtually no improvement in sample permeability.

The sealing layer at 280-300 mm was very difficult to erode and a maximum flow velocity of only 180 mm/min at an applied pressure differential of 21 psi was all that was attained.

A single permeability test result was obtained and the material behaviour assumed to be linear at such a low velocity (102 mm/min).

The permeabilities of the various layers as indicated by tests on both the full sample length and the sample minus the top 25 mm were as follows:-

	Full sample (2 points)	Sample minus top 25mm
(exposed) 0-216 mm	K_e = 30 mm/min.	K_e = 59 mm/min.
216-318 mm	K_e = 1.4 mm/min.	K_e = .8 mm/min.
318-450 mm	K_e = 21 mm/min.	K_e = 27 mm/min.

(Table 4.1, Figure 4.2b)

At such low flow rates hydraulic gradients within the layers outside the seal are very small and large errors can be expected. Under such circumstances there appears to have been little change in the sample permeability between tests on the full sample length and the single test on the sample with the top 25 mm removed. The full sample results have been plotted in Figure 4.5.

The sealing layer was seen to be only 20 mm thick (280-300 mm). If the pressure drop is not averaged over the distance between tappings 4 and 5 but assumed to take place over the 20 mms of the sealing layer the permeability within the layer will be of the order of 0.2 mm/min.

The material layers outside the sealing layer have all undergone an apparent reduction in permeability of the order of 80-90%. (0-216 mm, K_o = 310 mm/min, K_e = 30 mm/min) (318-450 mm, K_o = 108 mm/min, K_e = 21 mm/min). It is the author's opinion that these layers would clean up considerably if higher velocities of flow through the sample could be achieved. Being unable to improve the impermeable sealing layer (280 - 300 mm) has limited the available velocities and thus adversely affected the chances of improvement in less damaged layers of the sample material.

The sample was finally removed from the apparatus and inspected. Visual banding of the material was evident throughout the sample length. In some cases the bands covered the full cross sectional area whilst in others they appeared to be of variable depth and area. Distinct bands of finer looking material were recorded at the following distances from the sample top.

(i) 205 - 230 mm
(ii) 280 - 300 mm (distinct sealing layer)
(iii) 355 - 380 mm
(iv) 420 - 450 mm

The material from the sample was removed and sieve analyses carried out on the following four separate portions of the sample:

(i) 25 - 165 mm
(ii) 165 - 270 mm
(iii) 270 - 370 mm
(iv) 370 - 450 mm

The results of these analyses (Table 4.3 and Figure 4.8) revealed little variation in the grading of the material throughout the sample.

Material 3

Porosity = 40%

(original) Non-linear $K_o = 1/a$ = 609 mm/min, b/a^2 = .23
(Table 4.1, Figures 4.3a, 4.5)

See Table 4.2 and Figure 4.7. An effective seal formed gradually over 10 minutes which prevented any further loss of mud filtrate beyond 41 litres. The seal appears to be above tapping 1 and thus somewhere between 0 and 64 min. from the exposed face. Whole mud solids passed through the entire sample in the early stages of this test prior to the formation of the seal.

The mud was drained from the apparatus and then water was flushed through the test cell to remove all mud. Water was left standing 3 inches above the sample face for 68 hours prior to retesting for permeability.

Under a small pressure of about 5 psi water flowed through the sample. The pressure was increased to 20 psi and complete flushing of the sample was carried out for approximately 15 minutes. Permeability tests were then carried out on the full length sample (see Table 4.1 and Figure 4.3b).

The sample was removed from the apparatus and inspected. The remains of a distinct sealing layer in the top 10 mm of the sample were evident in patches over the cross sectional area of the exposed face of the sample. It is the author's opinion that the 10 mm sealing layer was broken up by the water flushing of the test cell which was carried out shortly after mud exposure ceased. In Test 003 the same procedure was applied but the sealing layer (not as distinct as in this test) remained intact and prevented any flow even under 15 psi applied pressure.

The top 25 mm were removed from the sample which was reinstalled and retested for permeability after flushing with water at pressures up to 20 psi. The flushing was extensive but no further improvement was noticeable.

The results of permeability tests on the exposed sample after maximum rehabilitation attempts were as follows:-

(exposed) Non-linear $K_e = 1/a = 566$ mm/min, $b/a^2 = 0.4$
(Table 4.1, Figures 4.3b, 4.5)

This would tend to indicate that only minor permanent damage beyond the top 10 mm seal has been done (permeability reduction of 7%).

However, for materials with $b/a^2 > 0.1$ the reliability of extrapolating non-linear equations ($i = aV + bV^2$) as determined from only 3 points to a value of permeability $K = 1/a$ is very low. In such cases, estimates of damage may be more reliably evaluated by comparing the hydraulic gradients necessary to achieve specified flow velocities. This was done for two velocities and the results were as follows:

(From Figure 4.5)

Specified flow Velocity mm/min.	Percentage change in permeability from the original
4000	-40%
2000	-31%

The entire sample material beyond the sealing top 10 mm layer has suffered an overall permanent reduction in permeability of the order of 35%.

3/16" Pea Gravel

Porosity = 38%

The material was placed in several layers, each of which exhibits differing flow behaviour.

(original) 64 - 114 mm Non-linear $K_o = 1/a = 250$ mm/min, $b/a^2 = .16$
114-216 mm Non-linear $K_o = 1/a = 1050$ mm/min, $b/a^2 = 1.5$
216-318 mm Non-linear Highly permeable K_o estimate 10,000 mm/min.
318-450 mm Non-linear $K_o = 1/a = 650$ mm/min, $b/a^2 = 1.9$
(Table 4.1 Figures 4.4a, 4.5)

See Table 4.2. Whole mud passed through the sample. After 4 minutes, 34 litres had been collected and no seal looked likely to be developing. The valve in the line below the sample was shut off and the sample thus isolated from any further mud infiltration. After 4 hours of mud flow exposure, (i.e. just prior to completion of the test) the valve was opened and the sample re-exposed to the pressurised mud flow. Whole mud again flowed through the sample at a rate which indicated that no seal had developed under the previous 4 hours of static conditions.

The sample was left covered with water for 68 hours after mud exposure had ceased. When retested for permeability, the mud sitting within the sample was quickly flushed out and the material was then retested for permeability.

For materials with $b/a^2 > 0.1$ the reliability of extrapolating non-linear equations ($i = aV + bu^2$) as determined from only 3 points to a value of permeability $K = 1/a$ is very low. Estimates of damage to the exposed sample material layers were thus evaluated by comparisons of the hydraulic gradients required to induce specified flow velocities within the material (From Figure 4.5).

Specified Flow Velocity mm/min	Percentage variation in permeability from the original material			
	64-114mm	114-216mm	216-318mm	318-450mm
4000	-24%	0%	0%	0%
2000	-32%	- 5%	- 3%	-10%

The least permeable original layer (64-114 mm, K_o = 250 mm/min) has suffered a permanent reduction in permeability of the order of 25-30%. The two more permeable original layers (114-216, K_o = 1050mm/min: 216-318,$K_o \approx$ 10,000 mm/min) have been virtually undamaged. The material beyond 318 mm (K_o = 650 mm/min) has suffered minor damage resulting in a reduction in permeability of the order of 5%.

If this sample had been exposed for a much longer period than 4 minutes, a seal may have eventually developed in the least permeable layer.

The sample was then removed from the apparatus and inspected. Visual banding of the material with depth in the sample was evident but no layers were clearly defined. The material was removed from the sample and sieve analyses carried out on the following four separate portions of the sample:

(i) 0 - 114 mm
(ii) 114 - 216 mm
(iii) 216 - 318 mm
(iv) 318 - 420 mm

The results of these analyses (Table 4.3 and Figure 4.8) revealed little variation in the grading of the material throughout the sample.

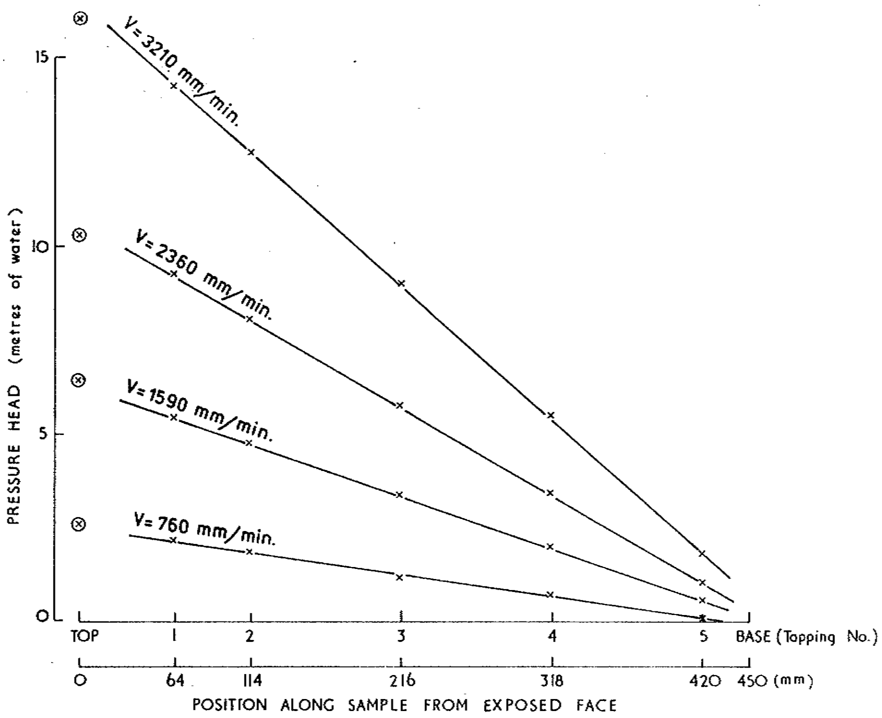


FIGURE 4·1(a) TEST 004. MATERIAL No. 2.

Pressure Distributions Before Exposure to Drilling Mud.

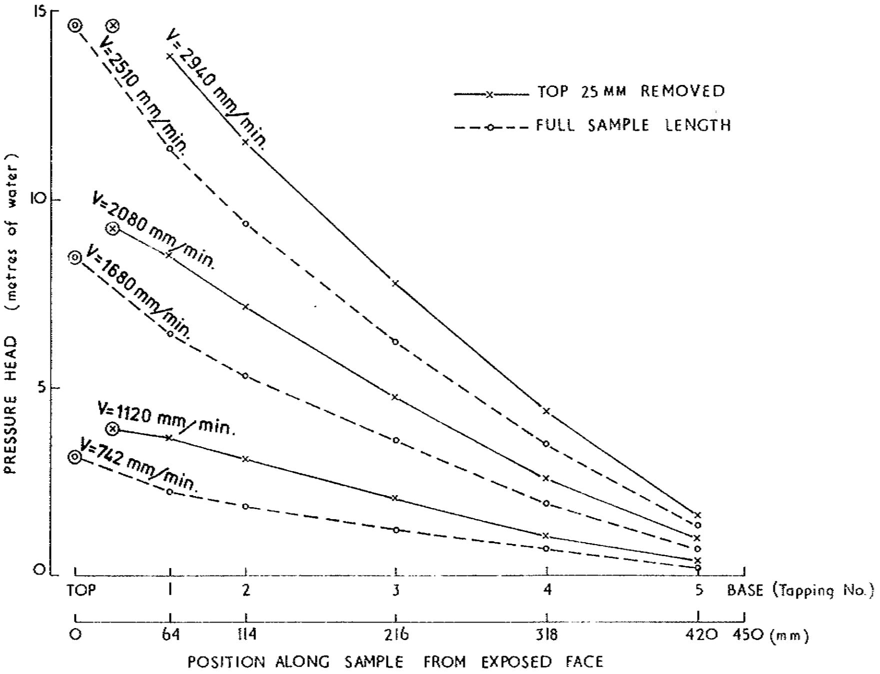


FIGURE 4·1(b) TEST 004. MATERIAL No. 2.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

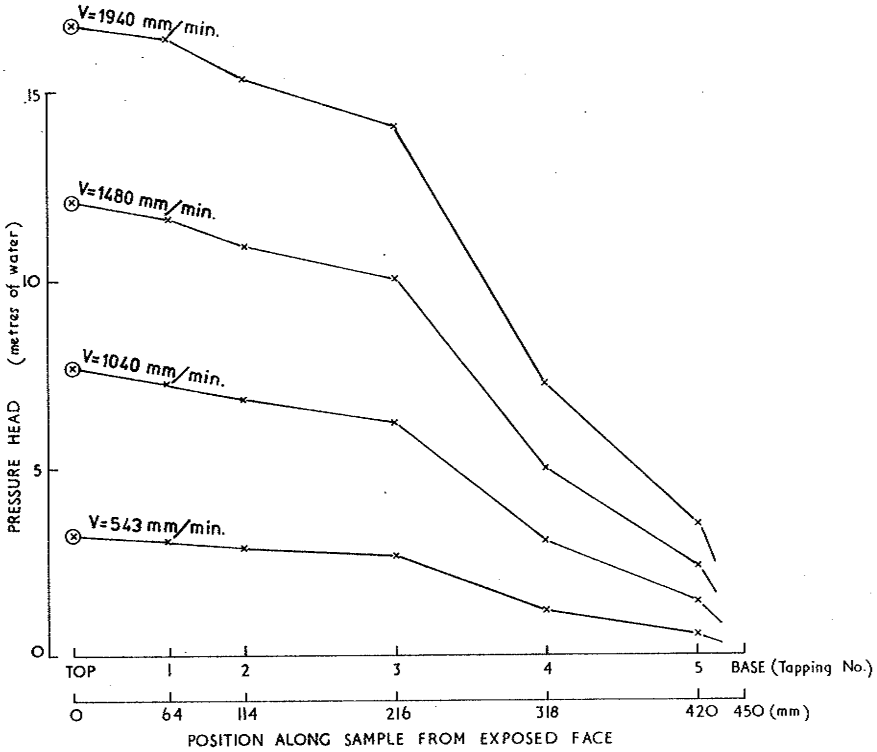


FIGURE 4·2(a) TEST 004. MATERIAL No. 6.

Pressure Distributions Before Exposure to Drilling Mud.

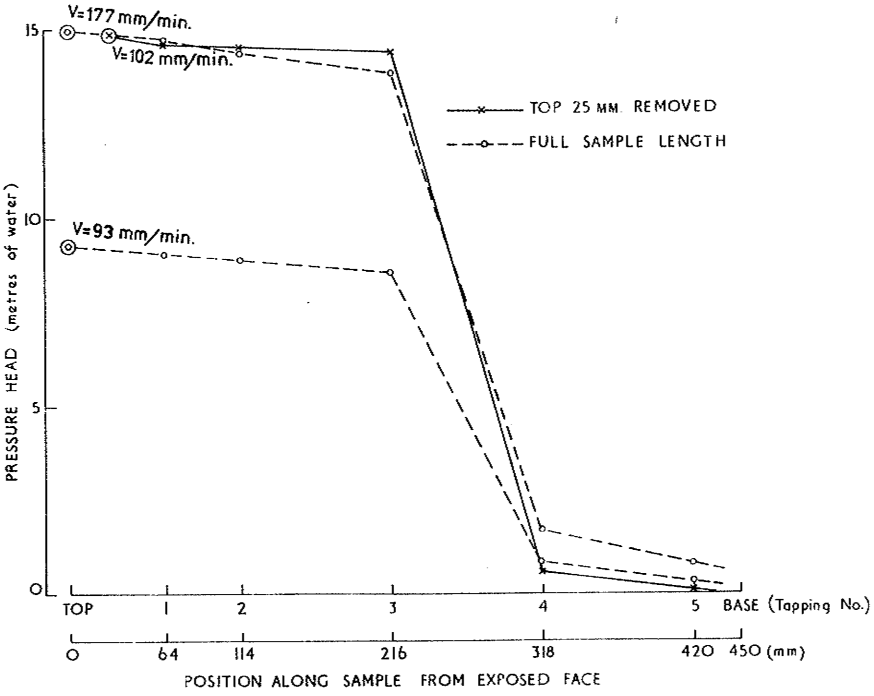


FIGURE 4·2 (b) TEST 004. MATERIAL No. 6.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

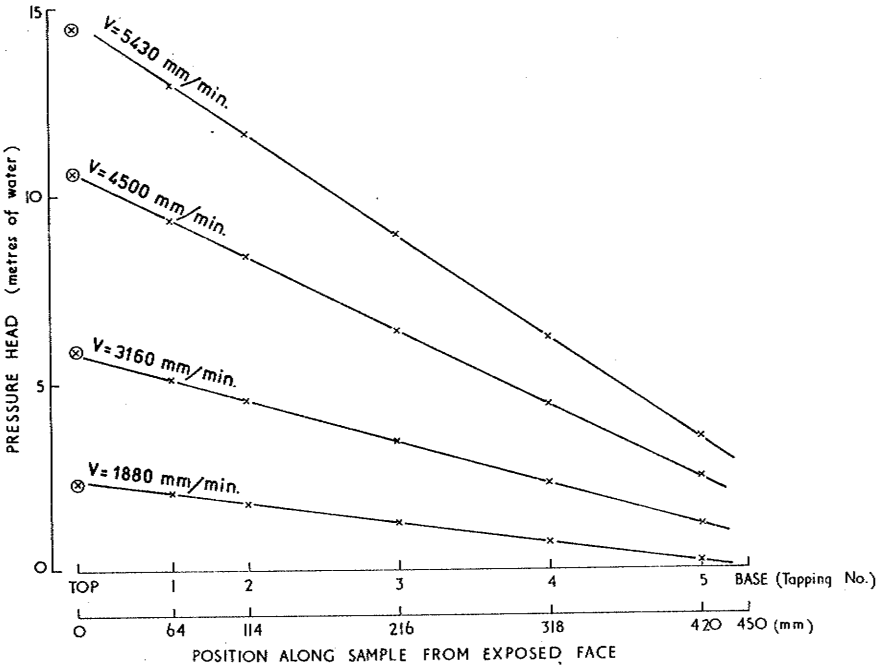


FIGURE 4·3(a) TEST 004. MATERIAL No. 3.

Pressure Distributions Before Exposure to Drilling Mud.

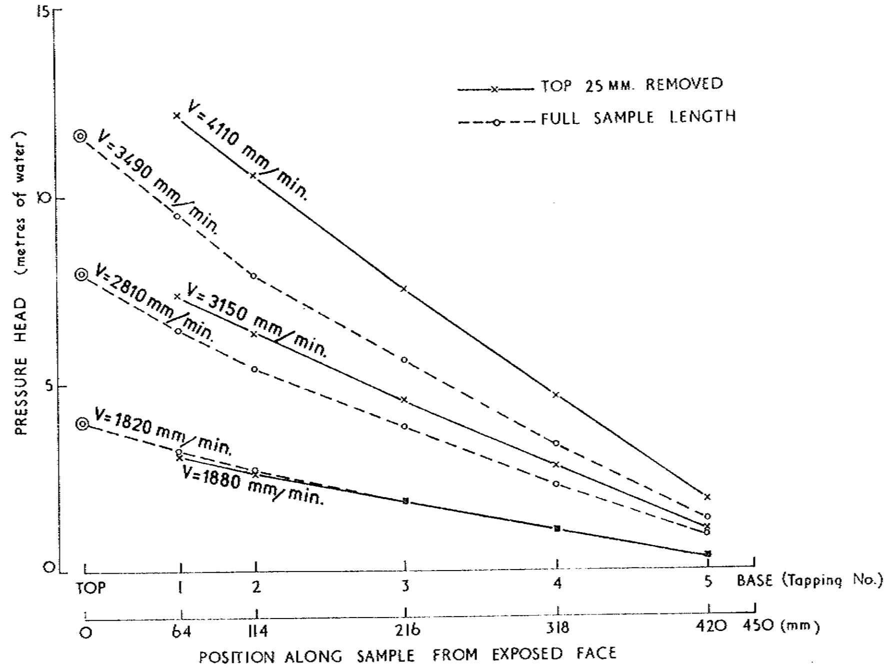


FIGURE 4·3(b) TEST 004. MATERIAL No. 3.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

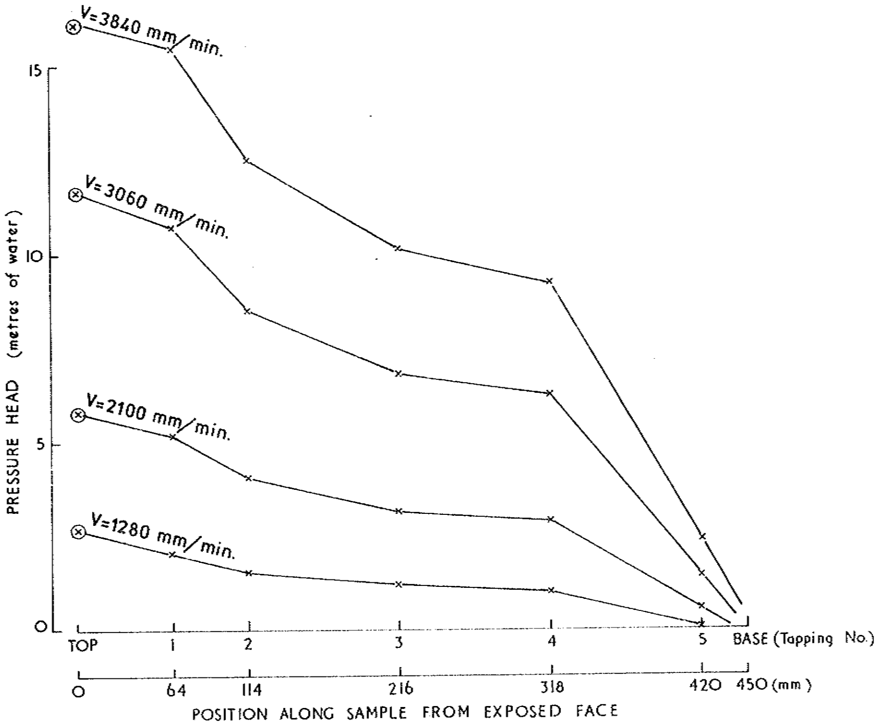


FIGURE 4·4(a) TEST 004. 3/16" PEA GRAVEL.
Pressure Distributions Before Exposure to Drilling Mud.

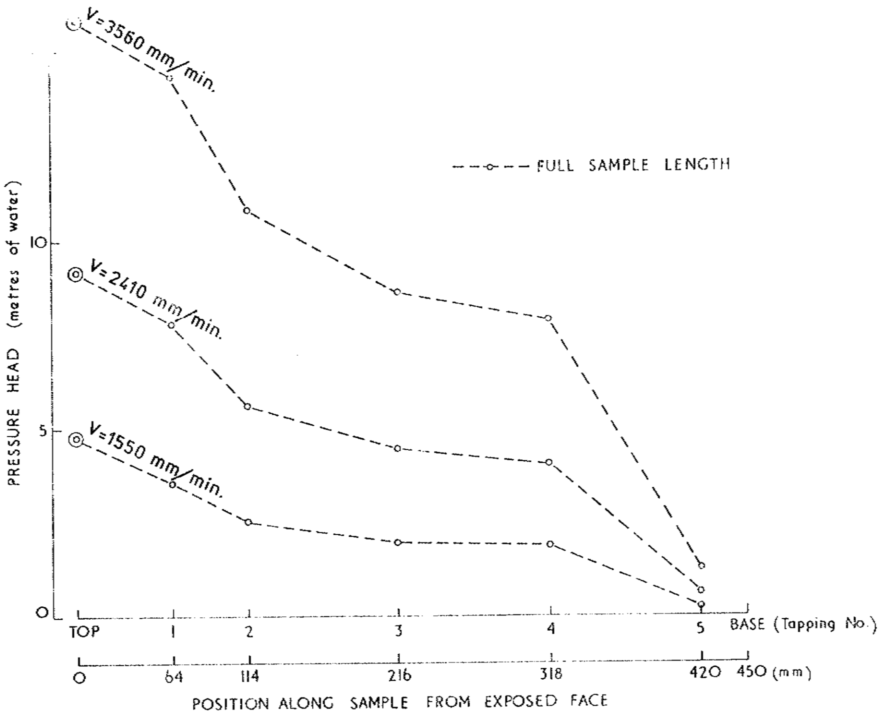
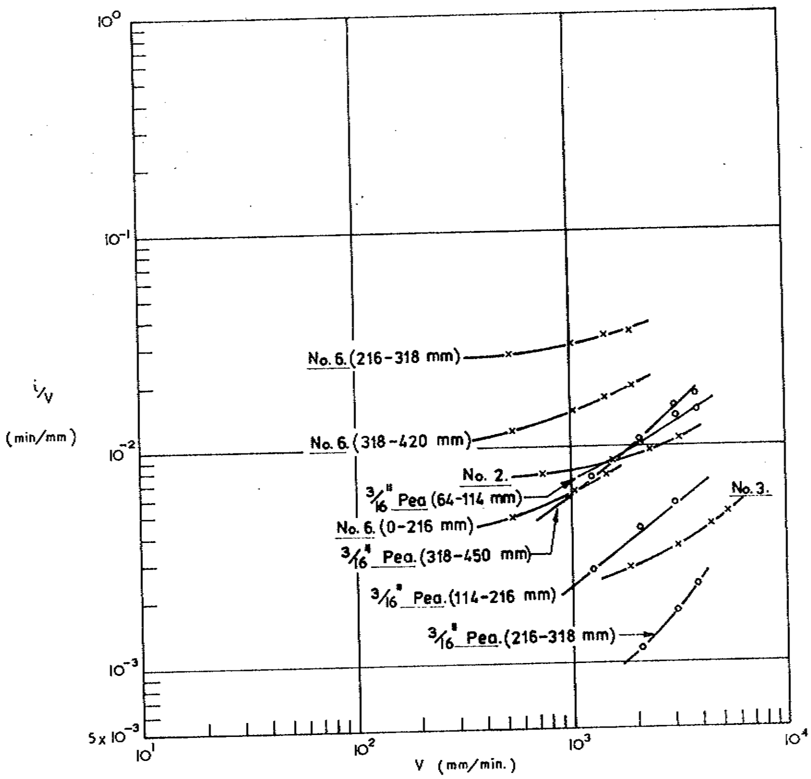
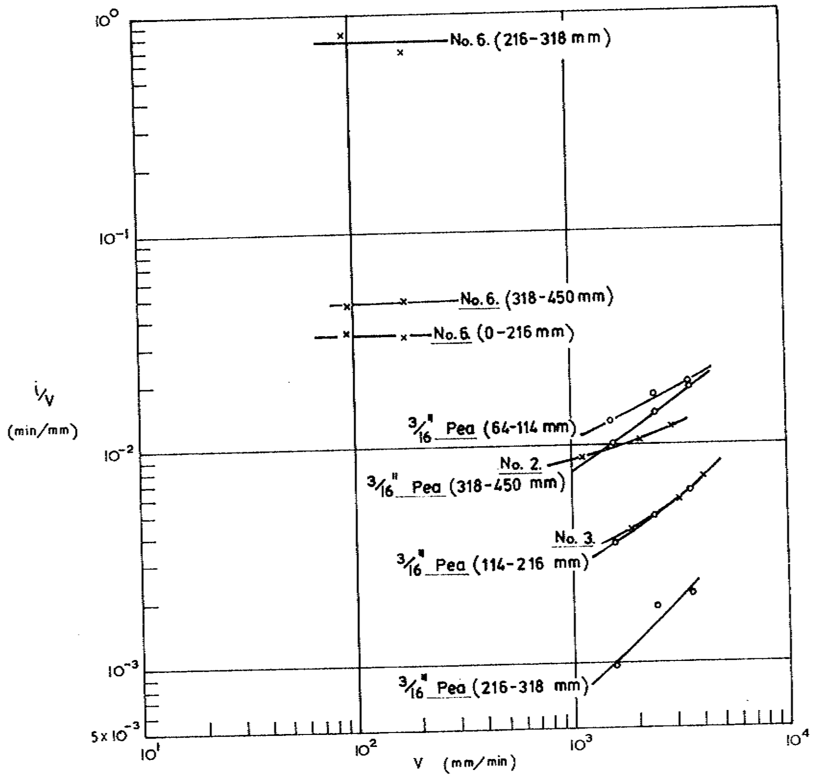


FIGURE 4·4(b) TEST 004. 3/16" PEA GRAVEL.
Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.



(a) Before Exposure to Drilling Mud



(b) After Exposure to Drilling Mud
Top 25 mm removed from sample

FIGURE 4·5 **TEST 004**

HYDRAULIC FLOW PROPERTIES OF TEST MATERIALS (i/V versus V)

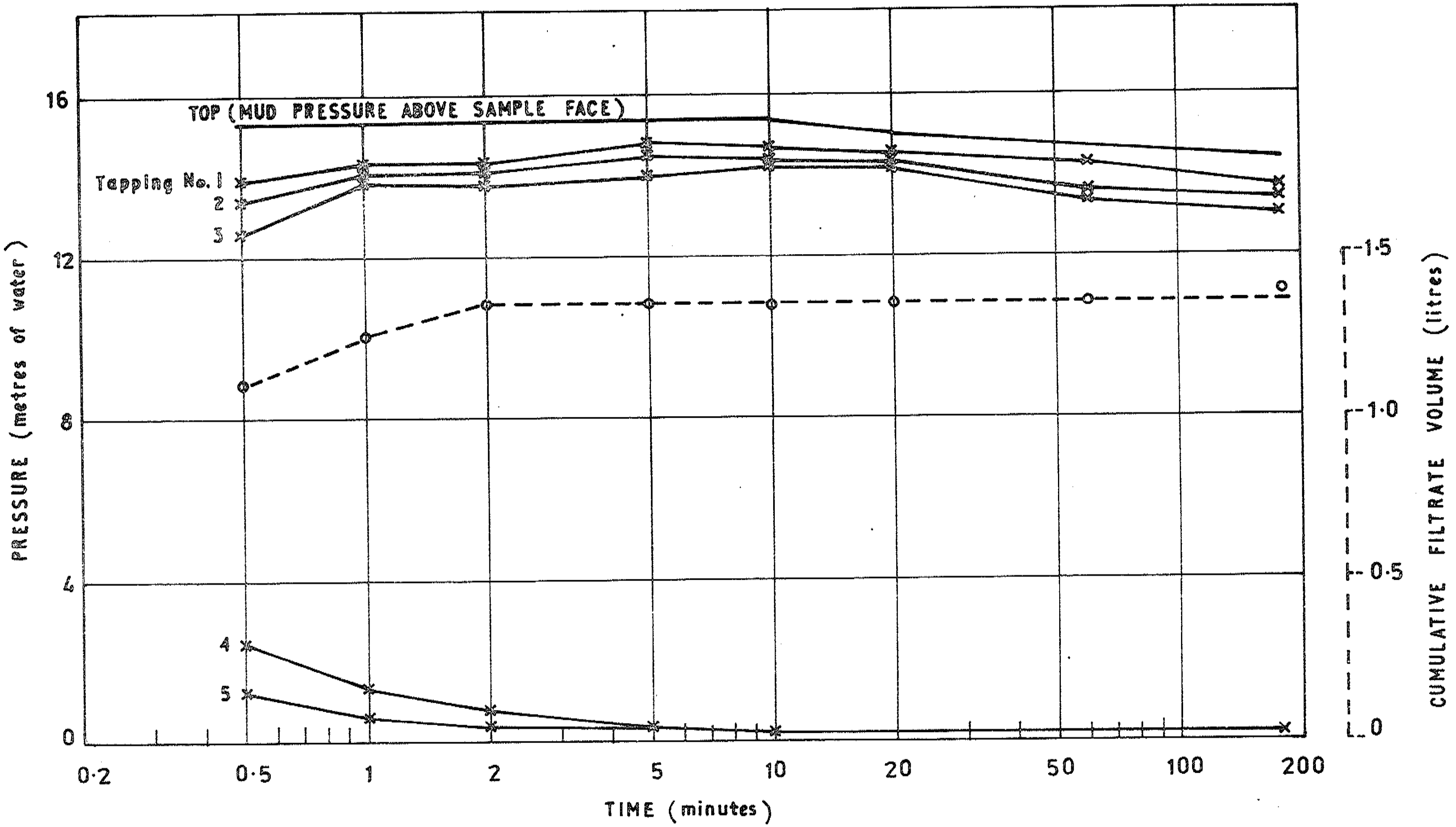


FIGURE 4·6: TEST 004 MATERIAL 6.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

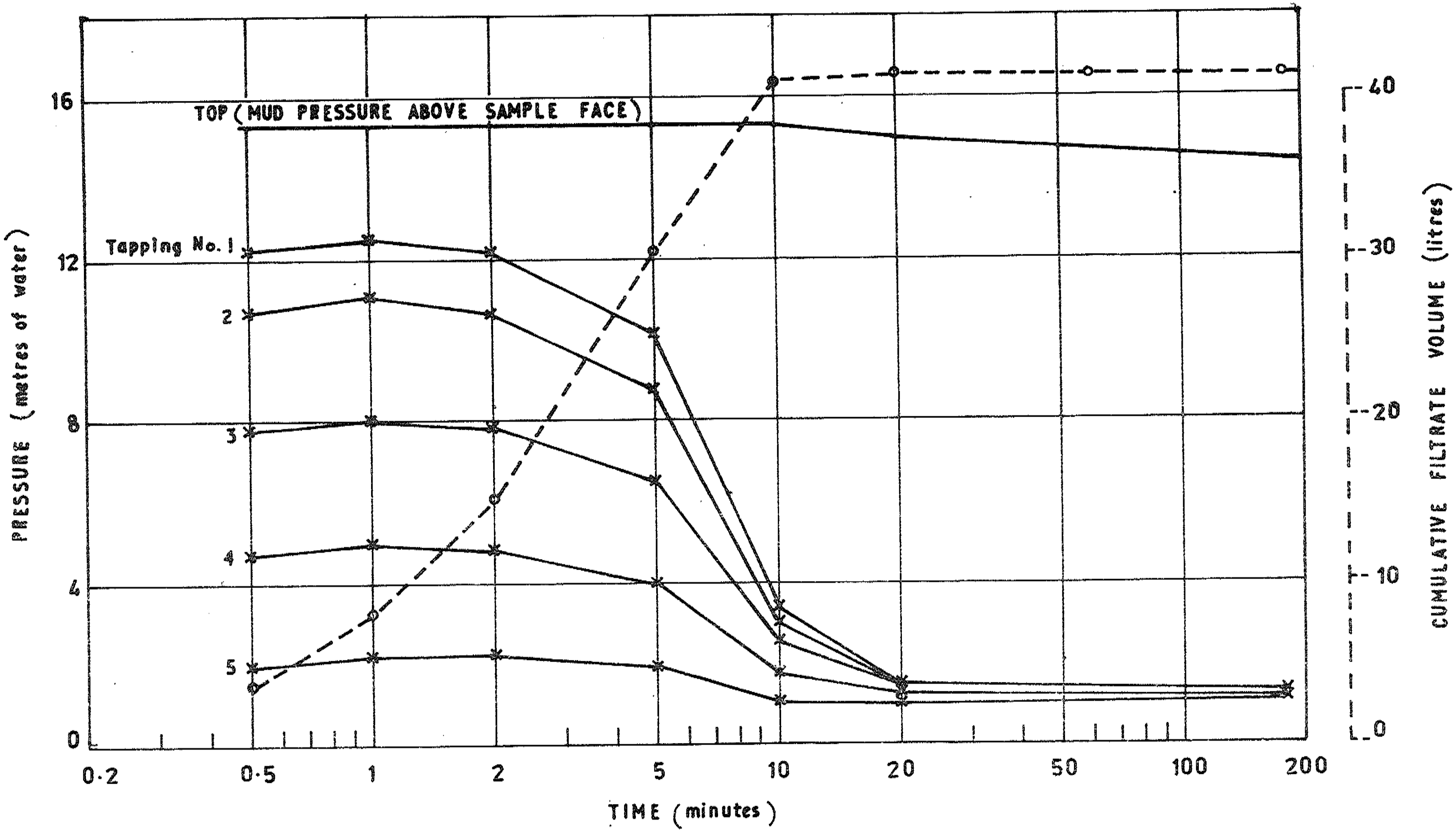
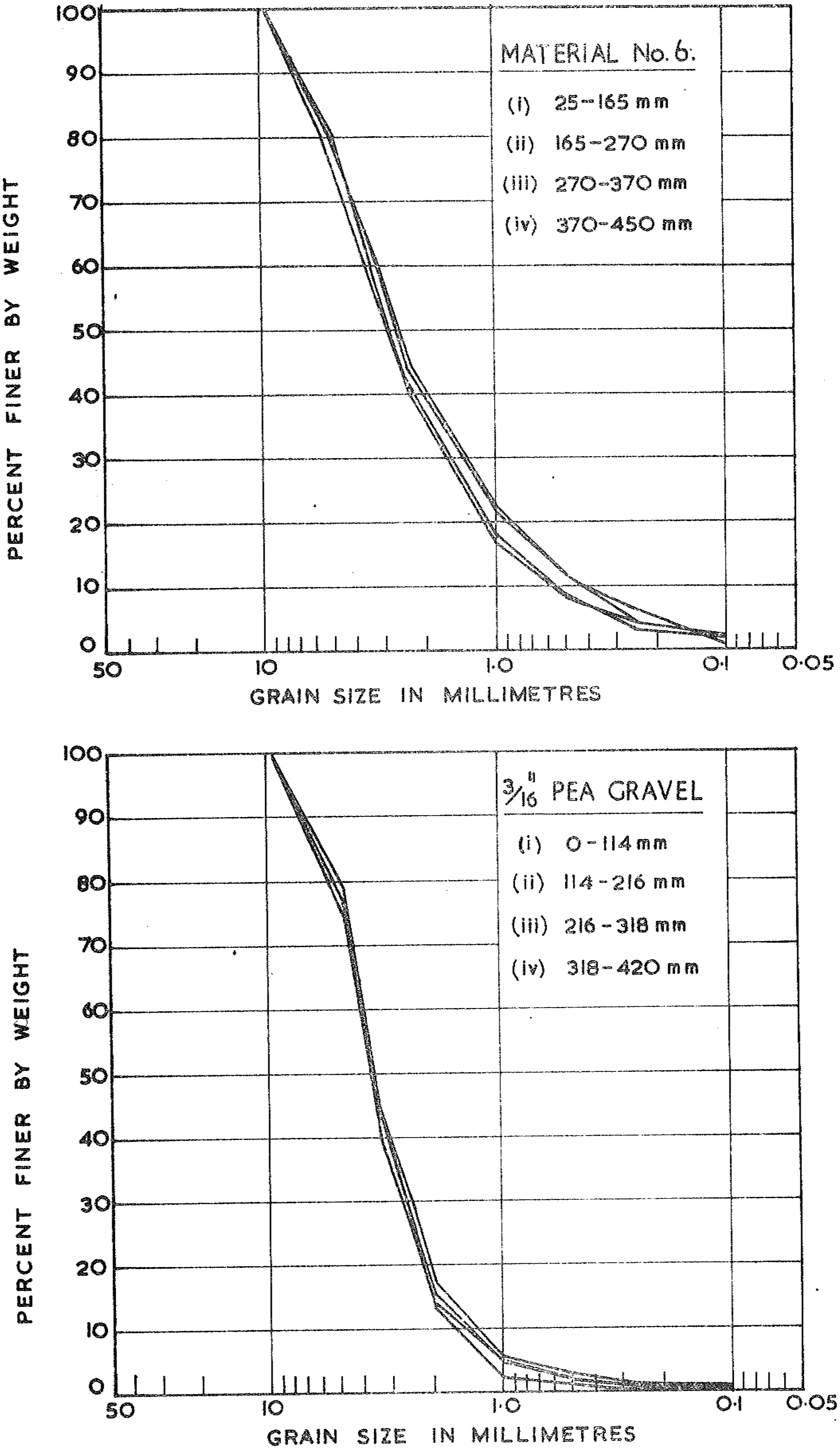


FIGURE 4·7: TEST 004 MATERIAL 3.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.



GRAVEL		SAND		
coarse	fine	coarse	medium	fine

FIGURE 4·8: GRAIN SIZE DISTRIBUTIONS OF SECTIONED PORTIONS OF MATERIAL 6 & 3/16" PEA GRAVEL

TABLE: 4.1 **TEST:** 004

Permeability testing of material samples

Values of pressure (metres of water) as recorded at various positions along the sample for a measured flow of water through the sample.

Material	Flow Rate litres/min	Velocity mm/min	Tapping No. Top		1	2	3	4	5
			Position along sample from datum (mm) 0	25	64	114	216	318	420
MATERIAL TESTS BEFORE EXPOSURE TO DRILLING MUD									
2	20.74	3210	16.07		14.24	12.54	9.01	5.48	1.77
	15.25	2360	10.40		9.26	8.07	5.74	3.41	1.01
	10.27	1590	6.40		5.42	4.73	3.34	1.96	0.51
	4.91	760	2.63		2.16	1.86	1.14	0.70	0.07
6	12.53	1940	16.83		16.45	15.31	14.11	7.25	3.47
	9.54	1480	12.06		11.66	10.90	10.08	4.98	2.33
	6.69	1040	7.61		7.25	6.81	6.24	3.03	1.39
	3.50	543	3.22		3.09	2.84	2.65	1.20	0.51
3	35.00	5430	14.71		12.92	11.66	8.95	6.11	3.47
	29.0	4500	10.86		9.33	8.38	6.37	4.35	2.40
	20.4	3160	6.09		5.11	4.54	3.41	2.27	1.14
	12.13	1880	2.54		2.08	1.77	1.26	0.70	0.19
3/16" Pea Gravel	24.78	3840	16.15		15.44	12.48	10.15	9.26	2.40
	19.72	3060	11.61		10.71	8.51	6.87	6.30	1.45
	13.56	2100	5.79		5.17	4.04	3.15	2.90	0.58
	8.29	1280	2.62		2.02	1.52	1.20	1.01	0.07
MATERIAL TESTS AFTER EXPOSURE TO DRILLING MUD Full Sample Length									
2	16.18	2510	14.56		11.34	9.33	6.24	3.47	1.33
	10.82	1680	8.51		6.43	5.30	3.59	1.89	0.70
	4.79	742	3.22		2.21	1.83	1.20	0.70	0.19
6	1.14	177	14.94		14.68	14.30	13.80	1.70	0.82
	0.60	93	9.27		9.01	8.82	8.51	0.82	0.38
3	22.50	3490	11.53		9.45	7.88	5.61	3.34	1.33
	18.12	2810	7.76		6.43	5.36	3.85	2.27	0.89
	11.73	1820	3.98		3.15	2.59	1.83	1.07	0.32
3/16" Pea Gravel	22.94	3560	15.84		14.30	10.78	8.63	7.88	1.26
	15.53	2410	9.12		7.75	5.61	4.48	4.04	0.63
	9.98	1550	4.73		3.53	2.52	1.96	1.83	0.25
MATERIAL TESTS AFTER EXPOSURE TO DRILLING MUD Top 25 mm removed from sample									
2	18.94	2940		14.63	13.80	11.53	7.75	4.35	1.64
	13.40	2080		9.19	8.51	7.12	4.73	2.59	0.95
	7.20	1120		3.90	3.66	3.09	2.02	1.07	0.32
6	0.66	102		14.86	14.56	14.43	14.30	0.57	0.19
3	26.53	4110			12.16	10.40	7.50	4.60	1.83
	20.30	3150			7.37	6.30	4.54	2.71	1.07
	12.11	1880			3.03	2.59	1.83	1.07	0.38

TABLE: 4.2 **TEST:** 004

Sample behaviour during time of exposure to drilling mud.

Material	Time (minutes)	Filtrate Volume (litres)	Tapping No.					
			Top	1	2	3	4	5
			Position along sample from datum (mm)					
			0	64	114	216	318	420
2	½			1.89	1.45	.57	.13	.13
	1	0.92	15.31	.82	.70	.44	.19	.19
	2	0.92	15.31	.70	.57	.32	.19	.19
	5	0.92	15.31	.44	.44	.32	.19	.19
	10	0.92	15.31					
	20	0.92	14.94	.26	.26	.26	.26	.26
	60	0.93	14.70	.26	.26	.26	.26	.26
	180	0.94	14.20	.26	.26	.26	.26	.26
6	½	1.10		13.80	13.29	12.41	2.46	1.20
	1	1.25	15.31	14.30	14.17	13.92	1.32	0.70
	2	1.35	15.31	14.30	14.05	13.67	0.82	0.32
	5	1.35	15.31	14.68	14.43	13.92	0.32	0.32
	10	1.35	15.31	14.68	14.30	14.17	0.19	0.19
	20	1.35	14.94	14.55	14.30	14.17	0.26	.13
	60	1.35	14.70	14.30	13.60	13.35	.19	.13
	180	1.39	14.20	13.60	13.40	13.00	.19	.13
3	½	3.80		12.28	10.77	7.75	4.73	1.96
	1	8.15	15.31	12.54	11.02	8.00	4.98	2.21
	2	15.10	15.31	12.16	10.65	7.88	4.85	2.21
	5	30.40	15.31	10.14	8.76	6.49	3.97	1.96
	10	40.80	15.31	3.46	2.96	2.46	1.70	1.07
	20	41.10	14.94	1.58	1.58	1.39	1.20	1.07
	60	41.10	14.70	2.59	2.46	1.96	1.45	1.07
	180	41.10	14.20	1.26	1.22	1.18	1.20	1.03
3/6" Pea Gravel	½	4.9		13.00	9.90	7.40	5.00	1.58
	1	~10.0	15.31	13.70	10.00	7.50	6.50	1.83
	2	19.0	15.31	13.55	9.65	7.25	6.37	1.83
	4	33.5	15.31					
	Did not look at all like sealing - sample isolated after 4 minutes							

Table 4.3: Grain Size Distributions of Sectioned Portions of Material 6 and 3/16" Pea Gravel

Material 6

Size (mm)	Percentage Finer by Weight			
	25-165mm	165-270mm	270-370mm	370-450mm
9.50	100	100	100	100
4.75	79.8	74.5	77.0	78.8
3.35	58.1	56.2	59.0	60.1
2.41	41.5	39.5	43.0	44.7
1.00	18.7	17.5	21.3	22.1
0.50	8.9	8.5	11.3	11.3
0.25	3.0	3.5	6.7	4.2
0.10	1.0	0.7	0.6	1.3
Pan	0.0	0.0	0.0	0.0

3/16" Pea Gravel

Size (mm)	Percentage Finer by Weight			
	0-114mm	114-216mm	216-318mm	318-420mm
9.50	100	100	100	100
4.75	74.5	79.3	79.3	76.8
3.35	40.0	46.0	44.8	45.1
2.41	22.8	28.1	24.7	25.1
1.98	15.4	14.7	13.3	16.7
1.00	6.1	5.0	1.9	5.1
0.50	2.7	2.2	0.8	2.2
0.25	1.01	1.0	0.4	1.1
0.10	1.0	1.0	0.4	0.8
Pan	0.0	0.0	0.0	0.0

V5 Test 005: Results and Observations

Mud was made up as $6\frac{1}{2}\%$ by weight Aquagel and 6% by weight of a prepared sand, the grading of which is shown in Figure 1.1. The sand added was of similar grading to a sample of sand which was carried by the drilling mud during rotary drilling of a typical hole in unconsolidated sediments in New South Wales.

The mud was circulated for 1 hour prior to starting the test and mud properties were maintained as follows for the duration of the test.

Temperature = 24°C

Specific gravity = 1.07

Marsh funnel viscosity = 50 seconds

Sand content = 1.75 - 2.25% (by volume)

API Filter press ($\frac{1}{2}$ area) $7\frac{1}{2}$ minutes = 2.1 cc
30 " = 4.2 cc

Filter cake thickness = 1/32" to 2/32"

Mud was circulated at a velocity of 120 ft/min. past the face of the sample materials and a pressure differential of approximately 12 psi was maintained for the exposure duration of 3 hours.

After 180 minutes of exposure to the mud flow, the test apparatus was isolated and all mud drained from above the samples. Water was then washed gently through the test cell for twenty minutes to clean all mud from the apparatus.

Water was added and each material flushed with clean water under applied pressures up to 20 psi until no further improvement in flow was noticeable with continued flushing.

Each sample material was retested for permeability in its present condition.

The samples were left covered with water for 16 hours

The samples were then removed, inspected, the top 25 mm removed from each material, reinstalled and retested for permeability to estimate the extent of damage caused by the mud.

Material 2

Porosity = 39%

(original) Non-linear $K_O = 1/a = 102$ mm/min, $b/a^2 = .024$
(Table 5.1, Figures 5.1a, 5.5)

See Table 5.2 and Figure 5.6. The behaviour of this material with time during exposure to the mud flow was unexpected and will now be discussed in detail.

Within the initial ½ minute of exposure to the mud there was definite evidence of the formation of an effective sealing layer somewhere above tapping 1 (hence between 0 and 64 mm). The pressure drop from 8.6 metres at the exposed face to 1 metre of water head at tapping 1 clearly indicates this seal's presence. The filtrate volume passed at ½ minute was 0.43 litres corresponding to a depth of penetration of mud filtrate of 170 mm. These results up to ½ minute are quite expected and compare well with results obtained in tests 002, 003, 004 for material 2 exposed to 6½% by weight Aquagel mud. In tests 002, 003 and 004 effective seals developed within the top 10 mm of the sample within the first ½ minute and the seals prevented filtrate losses beyond .19, .58 and .92 litres for the respective tests.

However, with time the effectiveness of the seal above tapping 1 steadily decreases until a relatively stable situation is reached after 50 minutes of exposure. As the seal in the upper 64 mm of the sample deteriorated there was a continued flow of filtrate through the sample.

See Figure 5.6. Pressure tappings numbers 3 and 4 were virtually unaffected until times of 2 and 10 minutes respectively. It is significant that the collected filtrate volumes at such times indicate mud penetration approximately coincidental with the tapping positions. It would appear that a front progressed with time through the material. Behind the front the material appears to be uniformly of lower permeability than the original material still ahead of the moving front of mud filtrate.

A stable flow situation appeared to be present beyond 50 minutes of mud exposure. There was still a steady loss of mud filtrate at a rate of approximately 3 cc/min. At 50 minutes the pressure drop from the face of the sample to tapping 1 has been reduced from the ½ minute value and was only from 8.9 to 4.5 metres of water head.

After the 180 minutes of mud flow exposure the mud was drained from above the sample and all mud gently washed from the test apparatus. Clean water was placed above the sample and pressure applied.

Under an applied pressure of 20 psi a minor degree of flushing and flow improvement was achieved.

The sample was retested for permeability (Table 5.1, Figure 5.1b). There was still evidence of a distinct sealing layer somewhere above tapping 1 (i.e. somewhere between 0 and 64 mm).

The sample was left covered with water for 16 hours and then removed and inspected.

There was a build-up of low permeability cakey material approximately 10 mm above the initial exposed face of the material. The lower portion of the test cell had large quantities of sand and mud lying in it. However, the cake build-up above the sample was firmly attached to the sample and was considered to be formed during the test.

A defined but not distinct layer of low permeability was evident below the original exposed face to a depth of approximately 5 to 10 mms.

The top 25 mm were removed from the sample which was then reinstalled and retested for permeability. Water flushing was carried out until maximum possible restoration of permeability was achieved.

The results of such tests were as follows:-

(exposed) 25-318 Non-linear $K_e = 1/a = 66$ mm/min, $b/a^2 = .092$
318-450 Non-linear $K_e = 1/a = 62$ mm/min, $b/a^2 = .037$
(Table 5.1, Figures 5.1b, 5.5)

There has been an apparent reduction in permeability of the order of 35-40% over the entire sample (excluding the severe damage in the upper 10 mm).

Alternative estimates of damage based on comparisons of the hydraulic gradients necessary to achieve specified flow velocities were made and are now given (from Figure 5.5).

Specified Flow Velocity mm/min	Percentage change in permeability from the original	
	25-318 mm	318-450 mm
1000	-66%	-51%
400	-62%	-46%

The following explanation for this material's behaviour during exposure to the sand contaminated Aquagel mud is offered.

In the very early stages a good seal developed just below the sample face. This seal was then broken down by the impingement of sand particles carried by the mud. The grading of the sand carried by the mud (Figure) was quite close to that of the sample material. Because of this there can be very little opportunity for whole mud solids to enter the voids of the sample and initiate an effective seal. A good seal did develop and may be considered a combination of a cake build-up above the exposed face and a layer within the top 10 mms immediately below the sample face.

The cake which built up above the sample face was probably being perpetually eroded and reformed during mud flow periods. This cake was not as impermeable nor as effective a seal as a distinct internal sealing layer. Without the formation of a distinct and effective sealing layer a small but continual steady flow of filtrate passed through the sample. The larger the filtrate flow the greater the depth of possible invasion of the very fine mud particles into the material.

In this case a total volume of 1.49 litres would indicate that mud filtrate has penetrated the entire sample depth.

Permanent damage has been done to the material beyond the upper 10 mm seal and a reduction in permeability of the order of 40-60% has occurred.

Material 6

Porosity = 30%

(original) 0-114 mm Non-linear $K_o = 1/a$ = 78 mm/min, $b/a^2 = .13$
114-216 mm Non-linear $K_o = 1/a$ = 13 mm/min, $b/a^2 = .013$
216-450 mm Non-linear $K_o = 1/a$ = 76 mm/min, $b/a^2 = .17$
(Table 5.1, Figures 5.2a, 5.5)

As can be seen the material had various layers of differing permeability throughout its length.

See Table 5.2 and Figure 5.7. The behaviour of the material with time of exposure to mud flow will now be discussed.

With time of exposure there was evidence of the formation of a sealing layer located somewhere above tapping 1 (i.e. somewhere between 0 and 64 mm). The effectiveness of this layer increased with time until at the end of the 180 minutes of exposure to the mud the seal accounted for a pressure drop from 9.25 metres to 0.7 metres of water and the filtrate flow rate had been reduced to 3 cc/minute.

It is interesting to note the behaviour of the less permeable material layer between 114 and 216 mm. In the first 2 minutes the pressure drop across this layer was a significant proportion of the total drop through the whole sample. However, after 2 minutes there was a steady reduction in the pressure drop across this layer concurrent with the increasing pressure drop above tapping 1 caused by the improved effectiveness of the sealing layer somewhere between 0 and 64 mm. After 50 minutes the head drop across 114-216 mm was relatively insignificant and was even surpassed by the head drop across 64-114 mm.

The sample beyond 64mm has apparently undergone a redistribution of flow resistance behaviour. The more permeable original layers have suffered considerable reduction in permeability to the extent that they now have flow resistance values of similar magnitude to the original least permeable layer.

The mud filtrate would have penetrated the entire sample length after 8 minutes when the collected filtrate volume was 0.9 litres.

After the 180 minutes of mud flow exposure the mud was drained from above the sample and all mud gently washed from the test apparatus. Clean water was placed above the sample and pressure applied.

Under an applied pressure of 20 psi a small degree of flushing and flow improvement was achieved.

The sample was retested for permeability (Table 5.1, Figure 5.2b). There was only a mild pressure drop above tapping 1 and the majority of resistance to flow was offered by the originally least permeable 114-216 mm layer. A considerable reduction in permeability of the material between 0-114 had occurred.

The sample was left covered with water for 16 hours and then removed and inspected.

There was a build-up of low permeability cakey material approximately 10 mm above the initial exposed face of the material sample. A defined but not distinct layer of low permeability was evident to a depth of 10mm into the sample.

The top 25 mm were removed from the sample which was then reinstalled and retested for permeability. Water flushing was carried out until maximum possible restoration of the sample was achieved.

The results of such tests were as follows:-

(exposed) 25-114 Non-linear $K_e = 1/a$ = 41 mm/min., b/a^2 = .087
114-216 Non-linear $K_e = 1/a$ = 14 mm/min., b/a^2 = .024
216-450 Non-linear $K_e = 1/a$ = 65 mm/min., b/a^2 = .19
(Table 5.1, Figures 5.2b, 5.5)

This sample was then removed and visually inspected. Banding was evident as could be expected from the original packing of the sample. However, there was a distinct layer of finer material visually apparent between 190 and 210 mm. Based on visual evidence the material between 190 and 210 mm appeared to be most impermeable whilst the material beyond 216 mm appeared to be more permeable than that between 25 and 114 mm.

The original permeability of the material between 114-216mm was averaged over the 102mm distance between the tappings numbers 2 and 3 although banding was visually apparent over this distance. It would appear that between 190 and 210mm there was an original layer of lower permeability than the remainder of the sample and that mud fines have been trapped in this layer making it more visually apparent when the final inspection was made. If the material were assumed to be in layers 25-190, 190-210, 210-450mm, then the estimated permeability of the exposed 190-210mm layer would be 4 to 5 mm/min.

Alternative estimates of damage based on comparisons of the hydraulic gradients necessary to achieve specified flow velocities were made from Figure 5.5 and are now given.

Specified Flow Velocity mm/min	Percentage change in permeability from the original		
	25-114	114-216	216-450
600	-55%	-10%	-29%
300	-50%	-4%	-23%

There has been considerably more damage done to the more permeable original layers. The original least permeable layer (114-216mm) has suffered only minor permanent damage of the order of 5%.

During exposure to the mud the more permeable layers (0-114mm and 216-450mm) were reduced in permeability to values of the order of the least permeable 114-216mm layer (i.e. K = 14 mm/min). These more permeable layers did rehabilitate considerably when flushed with clean water. However, permanent damage resulting in reductions in permeability of the order of 50% and 25% for the 25-114mm and 216-450mm layers respectively was caused by the flow of mud through the sample.

Material 3

Porosity = 39.5%

(original) Non-linear $K_o = 1/a = 516$ mm/min., $b/a^2 = .13$
(Table 5.1, Figures 5.3a, 5.5)

See Table 5.2. An effective seal was formed within ½ minute (somewhere in the top 64mm of the sample) which prevented any further loss of mud filtrate beyond 0.7 litres. The total collected filtrate volume of 0.7 litres indicates an estimated depth of mud filtrate penetration of 275mm.

After the 180 minutes of mud flow exposure the mud was drained from above the sample and all mud gently washed from the test apparatus. Clean water was placed above the sample and pressure applied.

Under an applied pressure of 20 psi a degree of flushing and flow improvement was achieved.

The sample was retested for permeability (Table 5.2, Figure 5.3b). The sealing layer above tapping 1 was still quite effective whilst the remainder of the sample showed very little change from the original.

The sample was left covered with water for 16 hours and then removed and inspected.

There was no visible variation in the material throughout the sample beyond the top 10mm. A distinct sealing layer was evident in the top 10mm of the sample. This layer contained considerable sand fines from the mud. The sealing layer was quite easily broken up when a slow flow of water from a hose was played directly upon it.

The top 25mm were removed from the sample which was then reinstalled and retested for permeability. Only minor water flushing was necessary to achieve optimum restoration of the sample. The permeability test results indicated:

(exposed) Non-linear $K_e = 1/a = 579$ mm/min, $b/a^2 = 0.21$
(Table 5.1, Figures 5.3b, 5.5)

This would indicate an improvement in permeability. However, for materials with $b/a^2 > 0.1$ the reliability of extrapolating non-linear equations ($i = aV + bV^2$) as determined from only 3 points to a value of permeability $K = 1/a$ is very low. In such cases, estimates of damage may be more reliably evaluated by comparing the hydraulic gradients necessary to achieve specified flow velocities. This was done for 2 velocities and the results were as follows (see Figure 5.5).

Specified Flow Velocity mm/min.	Percentage change in permeability from the original
6000	-12%
3000	0

With this sand contaminated Aquagel mud system an effective seal developed almost immediately within the top 10mm of the sample and the remainder of the sample suffered negligible permanent damage, if any.

Material 4

Porosity = 41%

(original) Non-linear K_o = 1/a = 1400 mm/min, b/a^2 = .38
(Table 5.1, Figures 5.4a, 5.5)

See Table 5.2. An effective seal was formed within $\frac{1}{2}$ minute (somewhere in the top 64mm of the sample) which prevented any further loss of mud filtrate beyond 0.8 litres. The total collected filtrate volume of 0.8 litres indicates an estimated depth of mud filtrate penetration of 300mm.

After the 180 minutes of mud flow exposure the mud was drained from above the sample and all mud gently washed from the test apparatus. Clean water was then flushed through the sample under an applied pressure of 20 psi. Only minor flushing was possible and the seal (somewhere in the top 64 mm) was still quite effective as illustrated by the permeability testing which was carried out at the time (see Table 5.2 and Figure 5.4b).

The sample was left covered with water for 16 hours and then removed and inspected.

A distinct sealing layer was evident in the top 10mm of the sample. This layer contained a large quantity of the sand which had been added to the Aquagel mud. The seal was quite easily broken up by gentle direct hosing. The remainder of the sample appeared no different from its original state.

The top 25mm were removed from the sample which was then reinstalled and retested for permeability. Only minor water flushing was necessary to obtain optimum restoration.

The permeability test results indicated -

(exposed) Non-linear K_e = 1/a = 2150 mm/min, b/a^2 = 1.5
(Table 5.1, Figures 5.4b, 5.5)

A more reliable estimate of damage was made by comparing the hydraulic gradients necessary to achieve specified flow velocities. This was done from the results shown in Figure 5.5.

Specified Flow Velocity mm/min.	Percentage change in permeability from the original
8000	-27%
4000	-12%

It is interesting to compare the behaviour of this material here with the results of Test 003. In Test 003 an uncontaminated $6\frac{1}{2}\%$ Aquagel mud would not seal the material at all and mud filtrate was easily washed from the sample, resulting in negligible permanent damage. The addition of sand to the mud has drastically altered its sealing ability. The sand-Aquagel mud system very quickly and effectively seals this material. However, the material in this test 005 suffered a permanent reduction in permeability of the order of 15-20%.

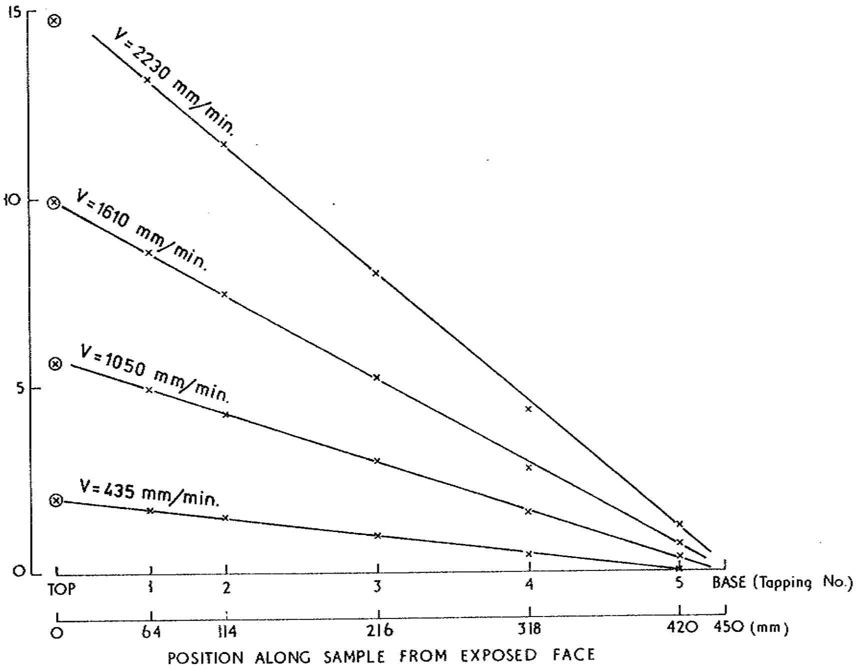


FIGURE 5·1(a) TEST 005. MATERIAL No. 2.

Pressure Distributions Before Exposure to Drilling Mud.

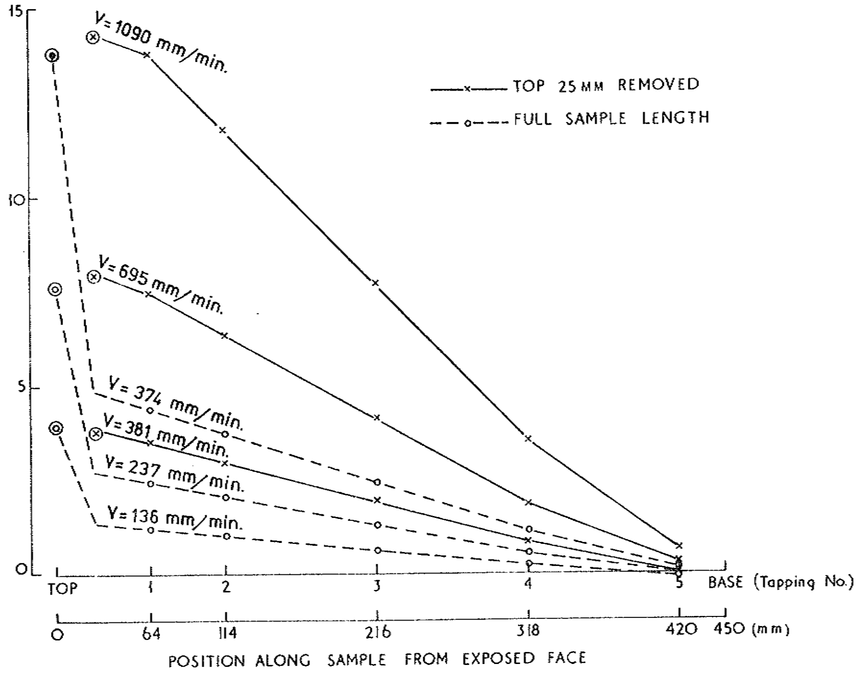


FIGURE 5·1(b) TEST 005. MATERIAL No. 2.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

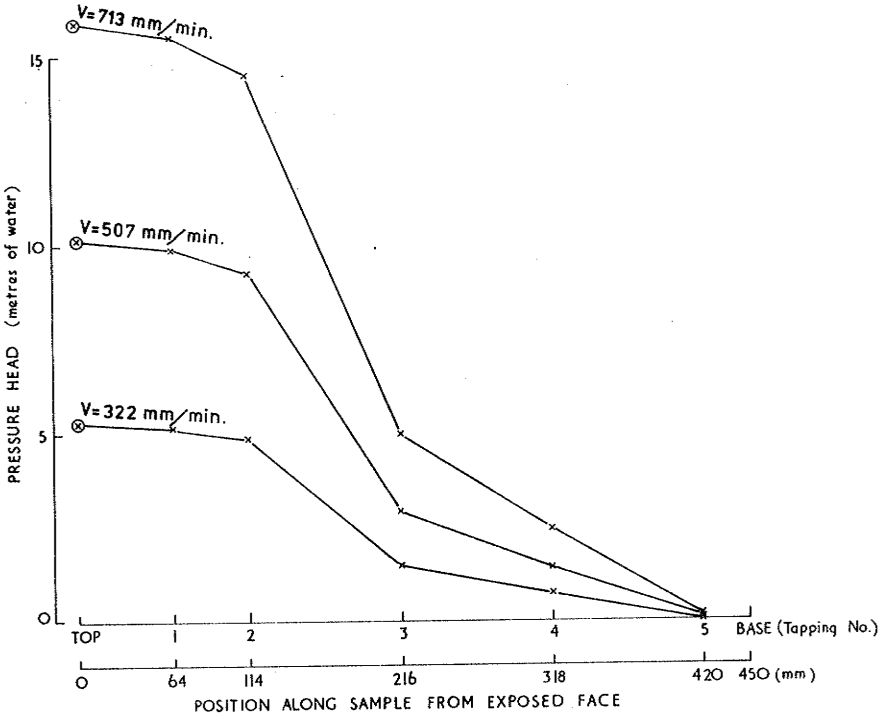


FIGURE 5·2(a) TEST 005. MATERIAL No. 6.

Pressure Distributions Before Exposure to Drilling Mud.

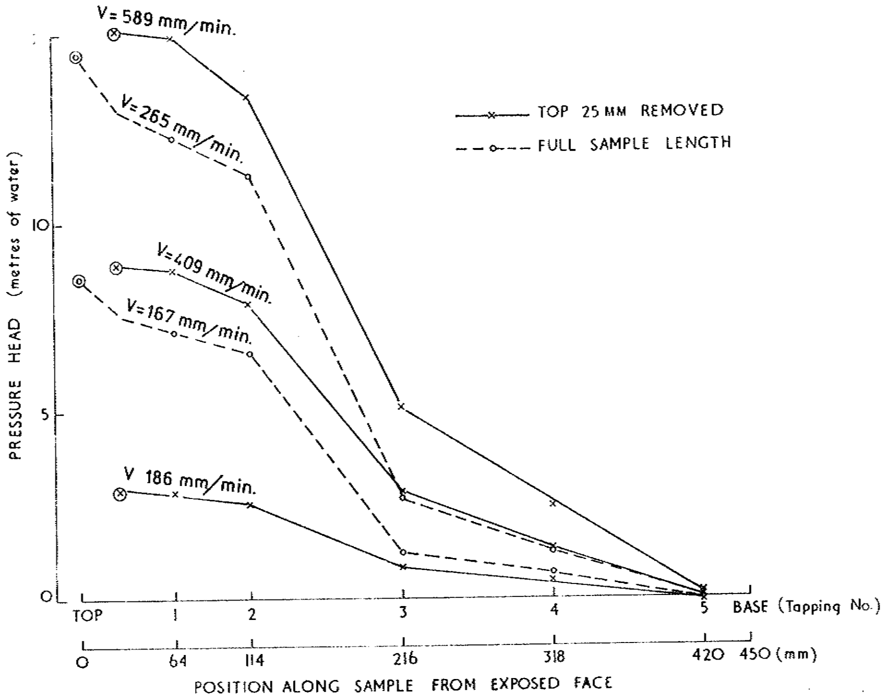


FIGURE 5·2(b) TEST 005. MATERIAL No. 6.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

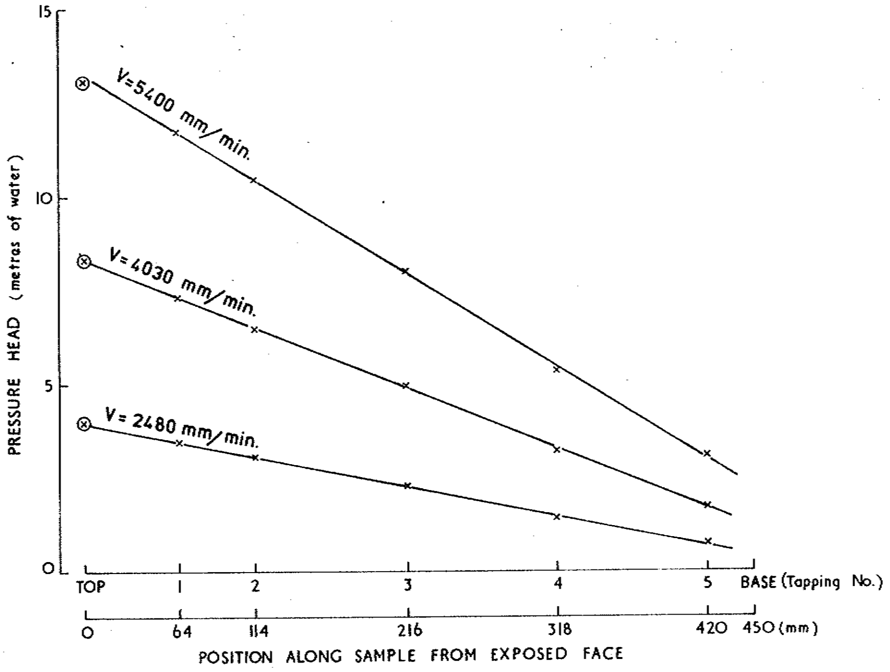


FIGURE 5·3(a) TEST 005. MATERIAL No. 3.

Pressure Distributions Before Exposure to Drilling Mud.

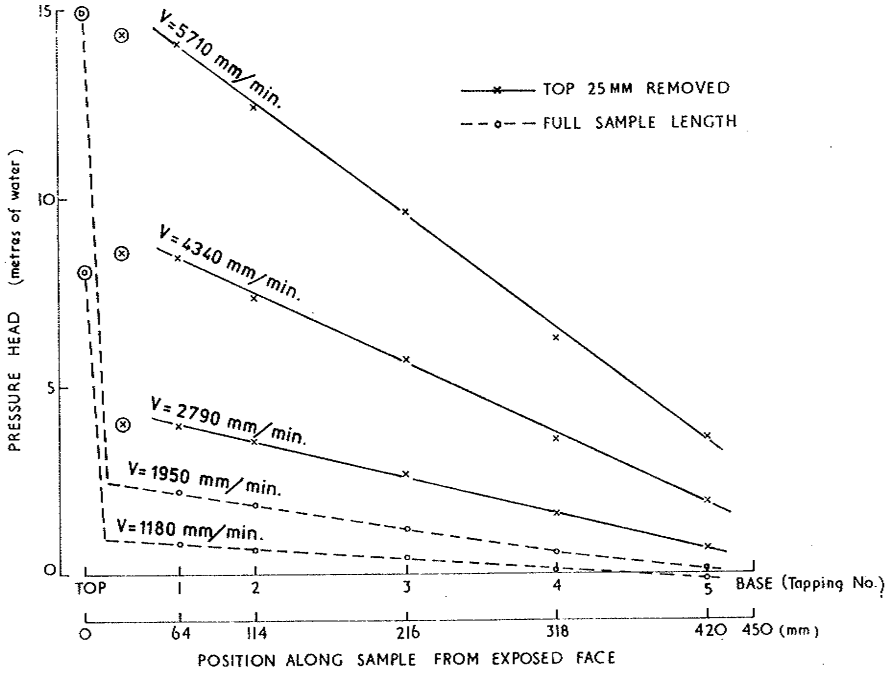


FIGURE 5·3(b) TEST 005. MATERIAL No. 3.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

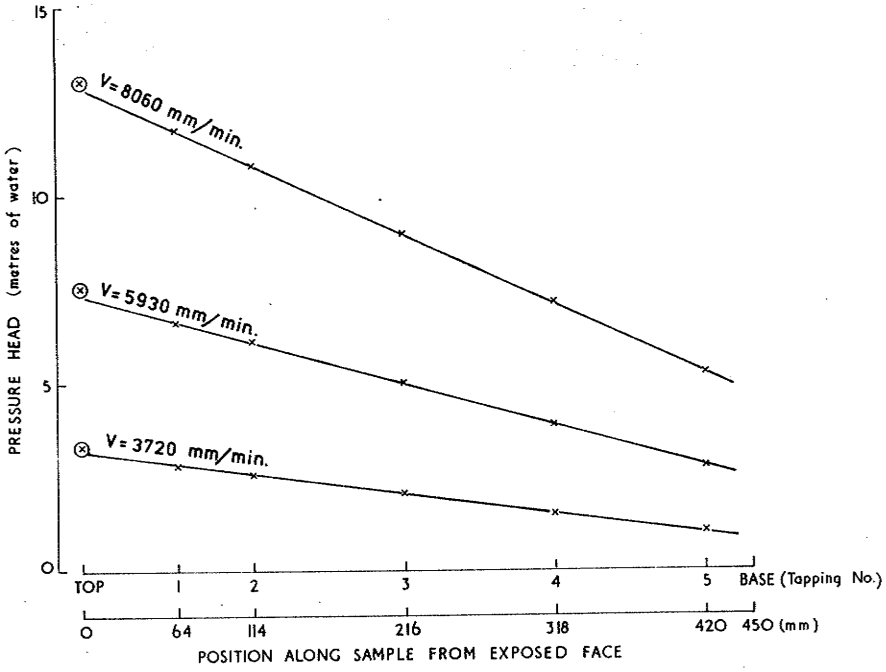


FIGURE 5·4(a) TEST 005. MATERIAL No. 4.

Pressure Distributions Before Exposure to Drilling Mud.

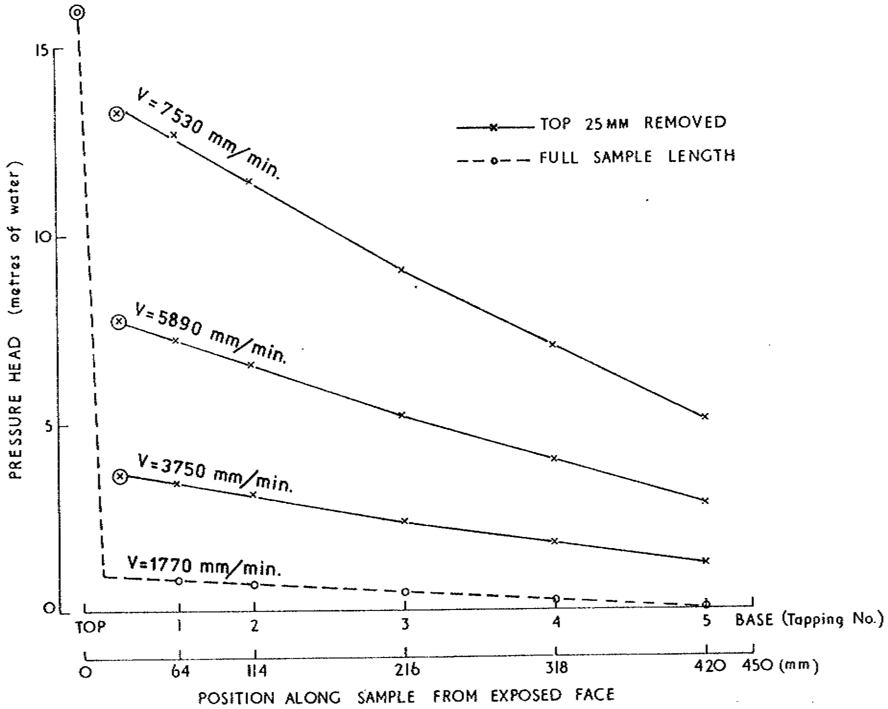
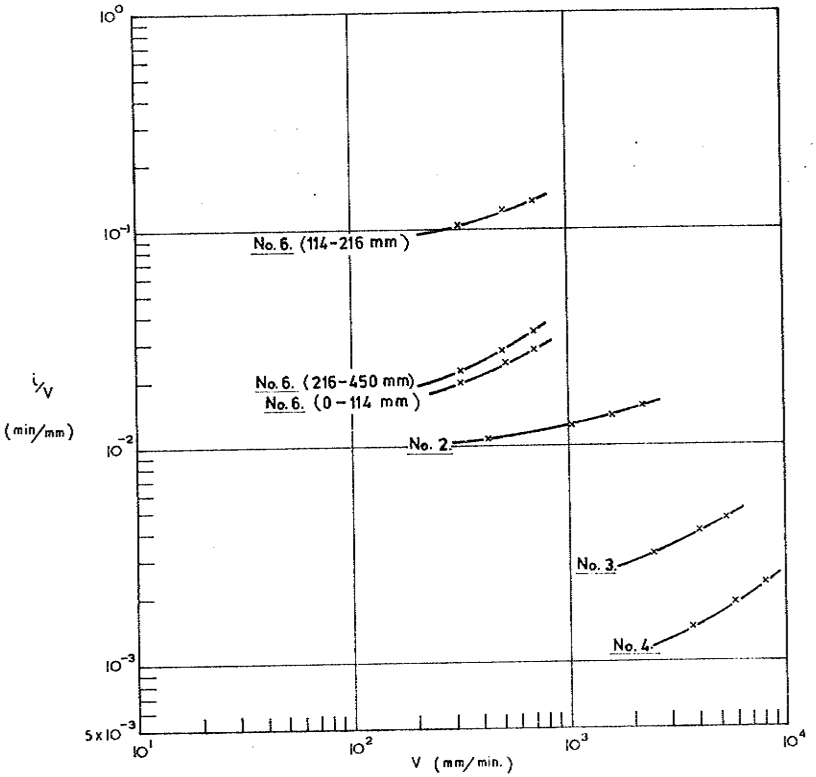
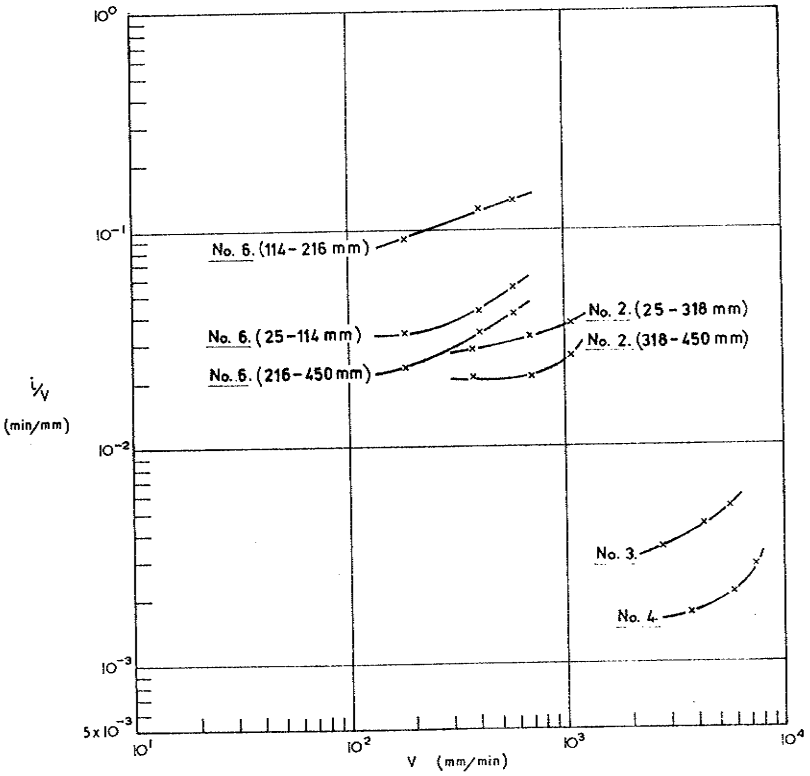


FIGURE 5·4(b) TEST 005. MATERIAL No. 4.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.



(a) Before Exposure to Drilling Mud



(b) After Exposure to Drilling Mud
Top 25 mm removed from sample

FIGURE 5·5 . TEST 005

HYDRAULIC FLOW PROPERTIES OF TEST MATERIALS (i/V versus V)

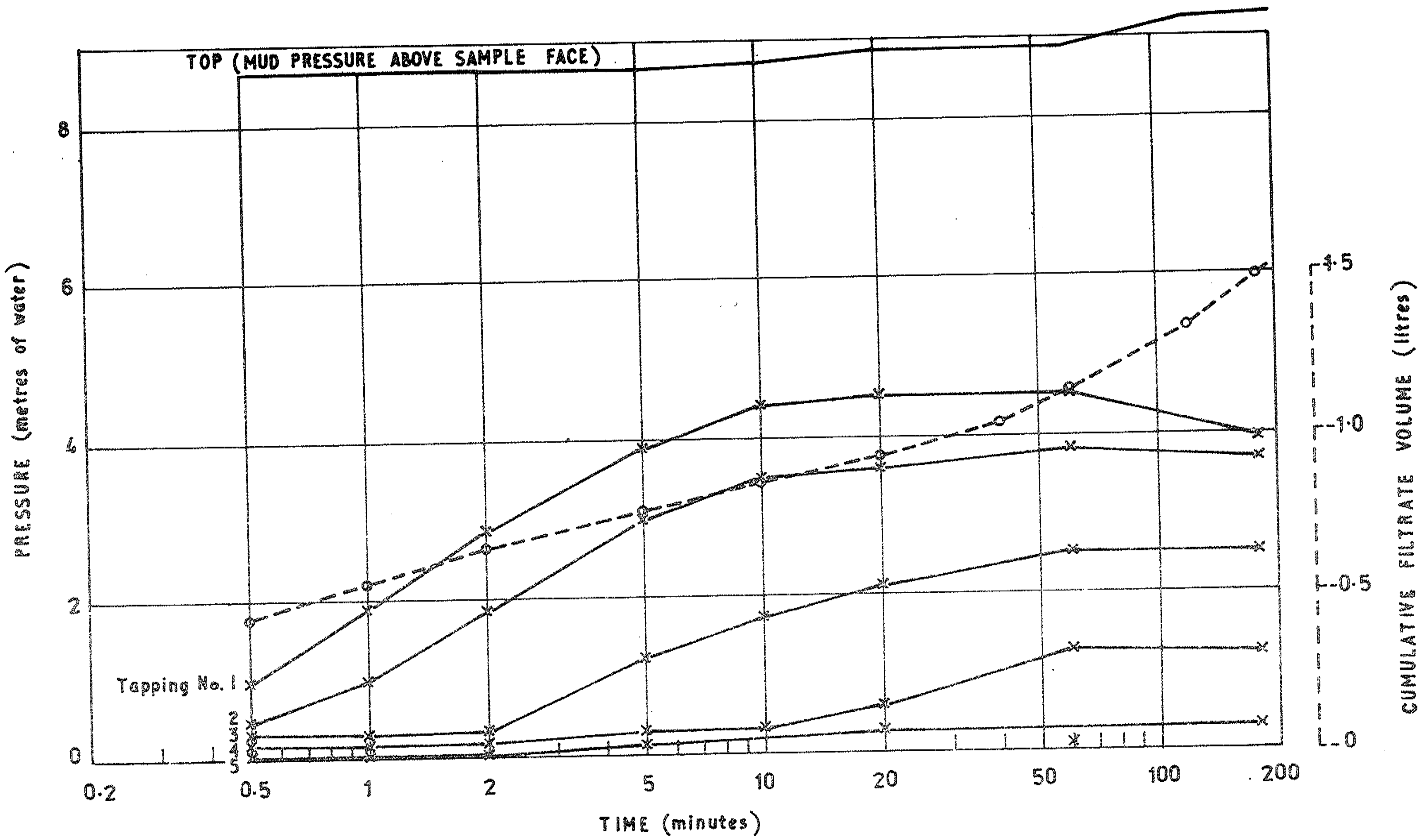


FIGURE 5·6: TEST 005 MATERIAL 2.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

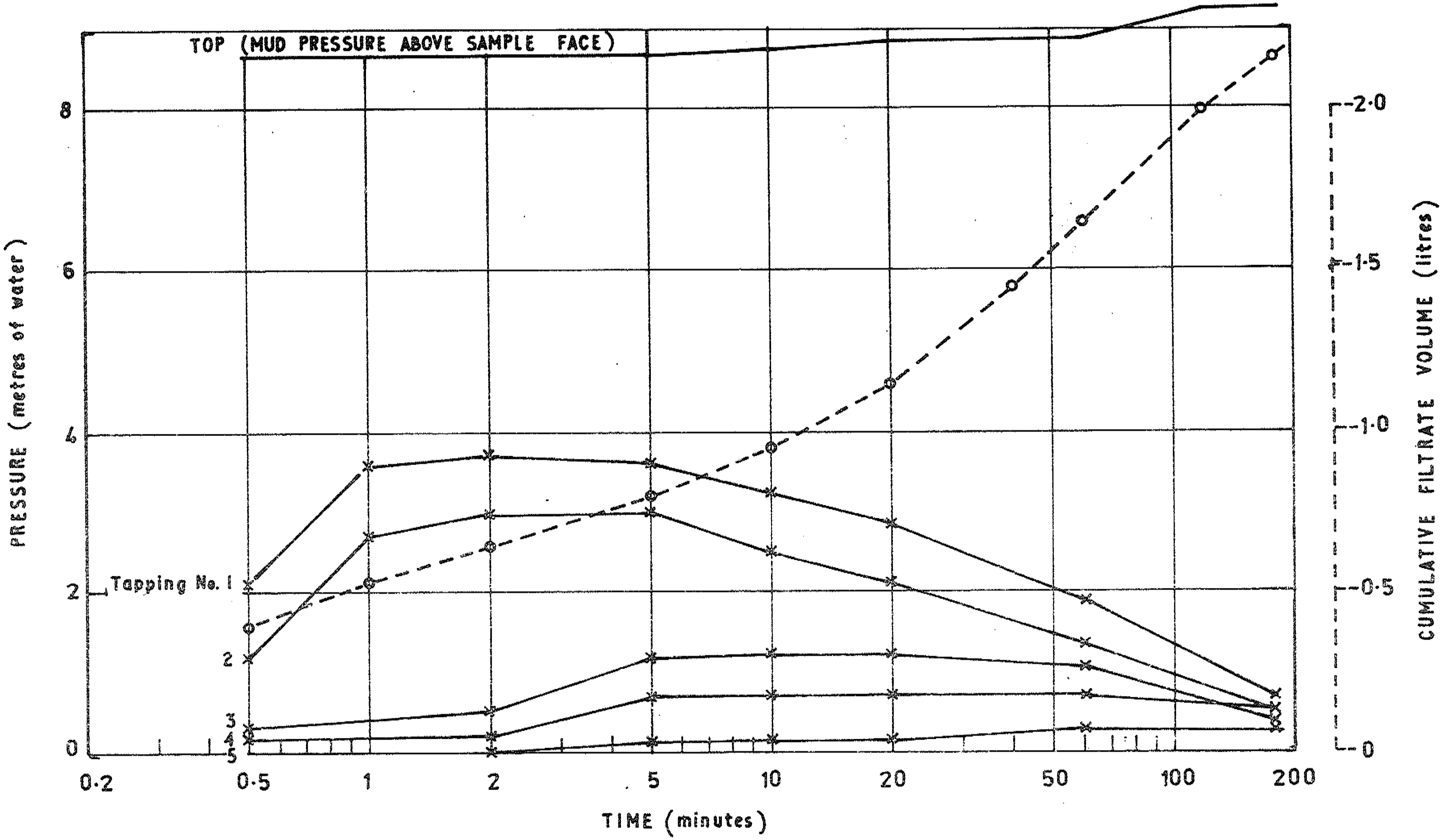


FIGURE 5·7: TEST 005 MATERIAL 6.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

TABLE: 5.1 **TEST:** 005

Permeability testing of material samples

Values of pressure (metres of water) as recorded at various positions along the sample for a measured flow of water through the sample.

Material	Flow Rate litres/min	Velocity mm/min	Tapping No.						
			Top		1	2	3	4	5
			Position along sample from datum (mm)						
			0	25	64	114	216	318	420
MATERIAL TESTS BEFORE EXPOSURE TO DRILLING MUD									
2	14.36	2230	14.71		13.11	11.41	7.94	4.29	1.20
	10.41	1610	9.95		8.57	7.44	5.17	2.71	0.70
	6.80	1050	5.57		4.85	4.22	2.90	1.52	0.32
	2.81	435	1.94		1.68	1.45	0.95	0.44	0.00
6	4.60	713	15.84		15.56	14.56	4.98	2.40	0.13
	3.27	507	10.18		9.89	9.26	2.90	1.39	0.07
	2.08	322	5.26		5.17	4.85	1.45	0.70	0.00
3	34.8	5400	13.05		11.72	10.40	8.00	5.30	3.03
	26.0	4030	8.29		7.31	6.43	4.92	3.15	1.70
	16.00	2480	3.90		3.47	3.03	2.27	1.39	0.70
4	52.0	8060	13.12		11.78	10.84	9.01	7.19	5.23
	38.27	5930	7.53		6.68	6.18	5.04	3.91	2.78
	24.0	3720	3.37		2.88	2.59	2.08	1.52	1.01
MATERIAL TESTS AFTER EXPOSURE TO DRILLING MUD Full Sample Length									
2	2.42	374	13.80		4.41	3.78	2.46	1.14	0.13
	1.53	237	7.76		2.46	2.08	1.33	0.57	0.00
	0.88	136	3.98		1.26	1.07	0.63	0.25	-0.06
6	1.71	265	14.56		12.29	11.28	2.65	1.26	0.07
	1.08	167	8.51		7.12	6.56	1.26	0.70	-0.06
3	12.6	1950	14.94		2.21	1.83	1.20	0.57	0.13
	7.6	1180	8.29		0.82	0.63	0.44	0.07	-0.12
	3.8	589	3.68		0.13	0.07	0.00	-0.19	-0.31
4	11.4	1770	15.77		0.89	0.70	0.44	0.26	0.07
	6.4	992	8.21		0.19	0.13	0.00	-0.06	-0.12
	3.6	558	3.83		-0.06	-0.12	-0.12	-0.19	-0.19
MATERIAL TEST AFTER EXPOSURE TO DRILLING MUD Top 25 mm removed from sample									
2	7.04	1090		14.33	13.80	11.78	7.75	3.53	0.63
	4.48	695		7.76	7.50	6.37	4.16	1.83	0.25
	2.46	381		3.68	3.53	2.96	1.96	0.82	0.07
6	3.80	589		14.94	14.93	13.30	5.11	2.46	0.19
	2.64	409		8.82	8.76	7.88	2.78	1.33	0.07
	1.20	186		2.85	2.84	2.52	0.82	0.51	-0.06
3	36.8	5710		14.33	14.05	12.41	9.64	6.24	3.59
	28.0	4340		8.51	8.38	7.37	5.74	3.53	1.89
	18.0	2790		3.98	3.97	3.53	2.65	1.58	0.70
4	48.6	7530		13.35	12.67	11.41	9.01	7.00	5.04
	38.0	5890		7.76	7.25	6.56	5.17	3.97	2.78
	24.2	3750		3.60	3.41	3.09	2.33	1.77	1.20

TABLE: 5.2 TEST: 005

Sample Behaviour during time of exposure to drilling mud.

Pressure (metres of water)

Material	Time (minutes)	Filtrate Volume (litres)	Tapping No. Top	1	2	3	4	5
			Position along sample from datum (mm) 0	64	114	216	318	420
2	½	.43	8.66	.95	.44	.32	.19	.07
	1	.55	8.66	1.83	.95	.32	.19	.07
	2	.66	8.66	2.84	1.83	.32	.19	.32
	5	.77	8.66	3.85	2.96	1.20	.32	.13
	10	.86	8.74	4.35	3.47	1.70	.32	.32
	20	.93	8.89	4.48	3.58	2.08	.57	.26
	60	1.13	8.89	4.48	3.78	2.52	1.26	.07
	180	1.49	9.25	3.90	3.66	2.46	1.20	.32
6	½	.40	8.66	2.08	1.20	.32	.19	.07
	1	.53	8.66	3.59	2.71	.19	.19	.07
	2	.65	8.66	3.72	2.96	.57	.13	.07
	5	.80	8.66	3.59	2.96	1.20	.70	.13
	10	.95	8.74	3.22	2.46	1.20	.70	.19
	20	1.15	8.89	2.84	2.08	1.20	.70	.13
	60	1.65	8.89	1.89	1.33	1.07	.70	.32
	180	2.16	9.25	0.70	.57	.44	.57	.32
3	½	.70	8.66	.07	.07	.07	.07	.07
	1	.70	8.66	.19	.07	.07	.07	.07
	60	.70	8.89	.19	.13	.07	.07	.07
	180	.70	9.25	.19	.19	.07	.07	.07
4	½	.80	8.66	.57	.32	.07	.07	.07
	1	.80	8.66	.32	.32	.07	.07	.07
	60	.80	8.89	.13	.07	.07	.07	.07
	180	.80	9.25	.07	.07	.07	.07	.07

V6 Test 006: Results and Observations

This test was run using the same materials and mud system as for test 005. The major difference was that the differential pressure was increased from 12 psi (test 005) to 21 psi (test 006).

The mud was approximately made up as 6½% by weight Aquagel and 6% by weight of a prepared sand, the grading of which is shown in Figure 1.1. The sand added was of similar grading to a sample of sand which was carried by the drilling mud during rotary drilling of a typical hole in unconsolidated sediments in New South Wales.

The mud was circulated for one hour prior to starting the test and mud properties were maintained as follows for the duration of the test.

Temperature = 24°C

Specific Gravity = 1.075

Marsh Funnel Viscosity = 56 seconds

Sand Content = 1.75 -2.25%(by volume)

API Filter Press (½ area) 7½ minutes = 2.4 cc
30 " = 5.1 cc

Filter cake thickness = 1/32" to 2/32"

Mud was circulated at a velocity of 120 ft/min. past the face of the sample materials and a pressure differential of approximately 21 psi was maintained for the exposure duration of 70 minutes.

After the 70 minutes of exposure to the mud flow, the test apparatus was isolated and all mud drained from above the samples. Water was then washed gently through the test cell for twenty minutes to clean all mud from the apparatus.

Water was added and the samples left under 3 inches of water for 20 hours. Pressures up to 20 psi were then applied to each sample and clean water flushing carried out until no further improvement in flow could be obtained.

Each sample was retested for material permeability in its present condition.

The samples were left covered with water for 54 hours.

The samples were then removed, inspected, the top 25 mm removed from each material, reinstalled and retested for permeability to estimate the extent of damage caused by the mud.

Material 2

Porosity = 39%

(original) Non-linear K_O = $1/a$ = 108 mm/min, b/a^2 = .034
(Table 6.1, Figures 6.1a, 6.5)

See Table 6.2 and Figure 6.6. The behaviour of the sample to the pressurised mud flow is similar to that exhibited in test 005. Only a brief report will be made here since a rigorous discussion was previously given in Section V5.

Within the initial $\frac{1}{2}$ minute of exposure to the mud there was definite evidence of the formation of an effective sealing layer somewhere above tapping 1 (hence between 0 and 64 mm). The filtrate volume passed at $\frac{1}{2}$ minute was .4 litres corresponding to a depth of penetration of mud filtrate of 160 mm.

However, with time the effectiveness of the seal above tapping 1 steadily decreased until after 5 minutes of exposure a stable condition was reached. As the seal in the upper 64 mm apparently deteriorated there was a continued flow of filtrate through the sample.

See Figure 6.6. Pressure tappings 3 and 4 were unaffected until times of 2 and 10 minutes respectively. The collected filtrate volumes at such times indicate estimated depths of mud filtrate penetration approximately coincidental with the tapping positions.

Beyond 5 minutes the situation appeared stable with a continuing small but steady flow of mud filtrate at a rate of approximately 3 cc/min. The pressure distribution clearly indicated that a reasonable seal still existed somewhere above tapping 1, but it was not as effective as it had been in the first $\frac{1}{2}$ minute.

After the 70 minutes of mud flow exposure the mud was drained from above the sample and all mud gently washed from the test apparatus. The sample was left covered with clean water for 20 hours.

The sample was then subjected to an applied pressure of 20 psi in attempts to break the seal and flush the material. Under this pressure a small trickle was all that could be obtained for the first few minutes until, quite suddenly the sealing layer's flow resistance appeared to break and the flow increased markedly. The initial muddy filtrate flow was very soon replaced by clean water and flushing was continued for 15 minutes.

The sample was retested for permeability (Table 6.1, Figure

6.1b). There was still evidence of a considerable degree of flow resistance by a sealing layer somewhere above tapping 1 (i.e. between 0 and 64 mm).

The sample was left covered with water for 54 hours and then removed and inspected.

There was a 15 mm thick built-up layer of sandy-clayey mud material above the initial exposed material face position. Virtually no evidence of any internal clogging below the sample face was found.

The top 25mm were removed from the sample which was then reinstalled and retested for permeability after further water flushing was carried out to ensure optimum restoration of material flow properties.

The results of such tests were as follows:-

(exposed): 25-316 Non-linear K_e = 1/a = 30 mm/min, b/a^2 = .035
316-450 Approximately Linear K_e = 50 mm/min.
(Table 6.1, Figures 6.1b, 6.5)

There have been apparent reductions in permeability of 72% and 54% for the 25-316 mm and 316-450 mm layers respectively.

Alternative damage estimates based on comparisons of necessary hydraulic gradients to achieve a velocity of 800 mm/min result in permeability reductions of 82% and 50% for the two layers.

An explanation of the initial formation, breakdown and subsequent stabilisation of a built-up impermeable cake above the sample face was given in Section V5.

Material 6

Porosity = 31%

(original) 0-114mm Linear K_o = 125 mm/min.
114-216 mm Non-linear K_o=1/a=25 mm/min, b/a^2 = .013
216-318mm Non-linear K_o=1/a = 117 mm/min, b/a^2 = .24
318-450mm Non-linear K_o= 1/a = 18 mm/min, b/a^2 = .04
(Table 6.1, Figures 6.2a, 6.5)

The sample had various layers of differing permeability throughout its length.

See Table 6.2 and Figure 6.7. The behaviour of the material with time of exposure to mud flow will now be discussed.

V6.4

Within ½ minute of exposure a significant seal had formed somewhere above tapping 1 (i.e. somewhere between 0 and 64 mm). The effectiveness of this sealing layer increased with time until at the end of 70 minutes exposure the seal accounted for a pressure drop from 13.05 metres to 0.44 metres of water and the filtrate flow rate had been reduced to 3½ cc/minute.

The magnitudes of the pressure drops across the various material layers indicated that these layers maintained the relative resistances to flow that they had exhibited in the original unexposed state.

The mud filtrate would have penetrated the entire sample length after 10 minutes when the collected filtrate volume was 0.9 litres.

After the 70 minutes of mud flow exposure the mud was drained from above the sample and all mud gently washed from the apparatus. The sample was left covered with water for 20 hours.

The sample was then subjected to an applied pressure of 20 psi. A reasonable flow of clean water was soon established and flushing was continued for 15 minutes.

The sample was retested for permeability (Table 6.1, Figure 6.2b). There was still evidence of a considerable degree of flow resistance by a sealing layer above tapping 1.

The sample was left covered with water for 54 hours and then removed and inspected.

There was a 10 mm thick built-up layer of sandy-clay mud material above the initial exposed face of the sample. Approximately 5mm of material had been removed from the top of the sample and replaced by the same sandy-clay mud cake which was evident above the face. Although mud was evident in the upper 20mm of the sample, virtually no evidence of any internal clogging layer within the original upper material layer was found.

The top 25mm were removed from the sample which was then reinstalled and retested for permeability after further water flushing.

The results of such tests were as follows:-

(exposed) 25-114mm Non-linear $K_e = 1/a = 26$ mm/min, $b/a^2 = .03$
114-216mm Non-linear $K_e = 1/a = 13$mm/min, $b/a^2 = .05$
216-318mm Non-linear $K_e = 1/a = 111$mm/min, $b/a^2 = 1.9$
318-450mm Non-linear $K_e = 1/a = 11$mm/min, $b/a^2 = .055$
(Table 6.1, Figures 6.2b, 6.5)

Based on these figures there has been considerable permanent damage done to the various layers of the material beyond the developed major seal. Permeability reductions of 80%, 50%, 5% and 40% were indicated for the 25-114, 114-216, 216-318 and 318-450mm layers respectively.

Alternative estimates of damage based on comparisons of the hydraulic gradients necessary to produce a specified flow velocity of 300mm/min were made. Permeability reductions of 85%, 70%, 75% and 60% were indicated for the respective layers.

Although a reasonably efficient sealing layer was formed by a cake build-up at the surface of the material, which reduced filtrate losses to a small value, permanent damage of the order of 60-80% was done to the various material layers.

Material 3

Porosity = 39%

(original) Non-linear $K_O = 1/a = 540$ mm/min, $b/a^2 = ..17$
(Table 6.1, Figures 6.3a, 6.5)

See Table 6.2. An effective seal was formed within $\frac{1}{2}$ minute (somewhere in the top 64mm of the sample) which prevented any further loss of mud filtrate beyond 0.2 litres. The total collected filtrate volume of 0.2 litres indicates an estimated depth of mud filtrate penetration of 80mm.

After the 70 minutes of mud flow exposure the mud was drained from above the sample and all mud gently washed from the test apparatus. The sample was left covered with water for 20 hours.

Under an applied pressure of 20 psi only a small flow rate could be induced and minor flushing was carried out.

The sample was retested for permeability (Table 6.1, Figure 6.3b). The developed sealing layer above tapping 1 was still extremely effective in reducing the flow through the material.

The sample was left covered with water for 54 hours and then removed and inspected.

A 10mm thick sandy-clay layer had replaced the top 10mm of the original material which had apparently been washed from the sample. A buildup of this same sandy clay cake was evident to a thickness of approximately 10mm above the original exposed face. The remainder of the sample appeared to be uniformly unaffected by the mud exposure.

The top 25mm were removed from the sample which was then reinstalled and retested for permeability. Only minor water flushing was necessary to achieve optimum restoration of the sample.

The permeability test results indicated:

(exposed) Non-linear $K_e = 1/a = 510$ mm/min, $b/a^2 = .17$
Table 6.1, Figure 6.3b, 6.5)

A permanent reduction of 5% in permeability had occurred.

Alternative damage estimates were made by comparing the hydraulic gradients necessary to achieve specified flow velocities. This was done using Figure 6.5 and resulted in the following permeability reductions:

Specified Flow Velocity mm/min.	Percentage change in permeability from the original
5000	-10%
2500	-8%

With the sand contaminated Aquagel mud an effective seal developed almost immediately in the top 10mm of the sample and the remainder of the sample suffered only minor permanent damage of the order of 5-10%.

Material 4

Porosity = 40%

(original) Non-linear $K_o = 1/a = 1700$ mm/min, $b/a^2 = .69$

See Table 6.2. An effective seal was formed within $\frac{1}{2}$ minute (somewhere in the top 64 mm of the sample) which prevented any further loss of mud filtrate beyond 1 litre. The total collected filtrate volume of 1 litre indicates an estimated depth of mud filtrate penetration of 390 mm.

After the 70 minutes of mud flow exposure the mud was drained from above the sample and all mud gently washed from the test apparatus. The sample was left covered with water for 20 hours.

Under an applied pressure of 20 psi no flow could be forced through the sample. The sealing layer above tapping 1 was still extremely effective (see Table 6.1 and Figure 6.4b).

The sample was left covered with water for a further 54 hours before being removed and inspected.

A 10mm thick sandy clay sealing layer had replaced the top 10mm of original material which had apparently been washed from the sample. A build-up of less impermeable sandy clay material was evident 10mm above the original exposed face. Evidence of mud filtrate was seen throughout the entire sample length.

The top 25mm were removed from the sample which was then reinstalled and retested for permeability. Only minor water flushing was necessary to achieve optimum restoration of the sample.

For materials with $b/a^2 > 0.1$ the reliability of extrapolating non-linear equations ($i = aV+bV^2$) as determined from only three points to a value of permeability $K = 1/a$ is very low. In such cases, estimates of damage may be more reliably evaluated by comparing the hydraulic gradients necessary to achieve specified flow velocities. This was done using the data of Figure 6.5.

Specified Flow Velocity mm/min	Percentage change in permeability from the original	
	25-216mm	216-450mm
6000	-50%	-34%
4000	-42%	-21%

These results are consistent with test 005. In particular the note given in Section V5 regarding the difference in behaviour of the material due to the sand addition to the Aquagel mud is relevant.

With the uncontaminated Aquagel 6½% mud no seal develops but the material is quite easily flushed clean with no resultant permanent damage.

The sand-Aquagel mud effectively seals the material in the top 10mm, but, permanent damage to the remainder of the material can be done resulting in permeability reductions of the order of 20-50%.

Note

The reported 10-15mm thick buildup of sandy-clay material above the face of each sample should be treated with suspicion. When the mud flow was stopped, it generally took about 10 minutes before the mud could be drained from above the faces of the samples. In that quiescent time it was quite possible for sand to drop out of the mud and settle in the test cell. Evidence of the same sandy clay material reported as cake build-up was in fact found to a depth of 10-20mm in the pipe when dismantled after test completion.

At the time of inspection this fact was not recognised and relative estimates of the impermeability of the reported cake build-ups were not made.

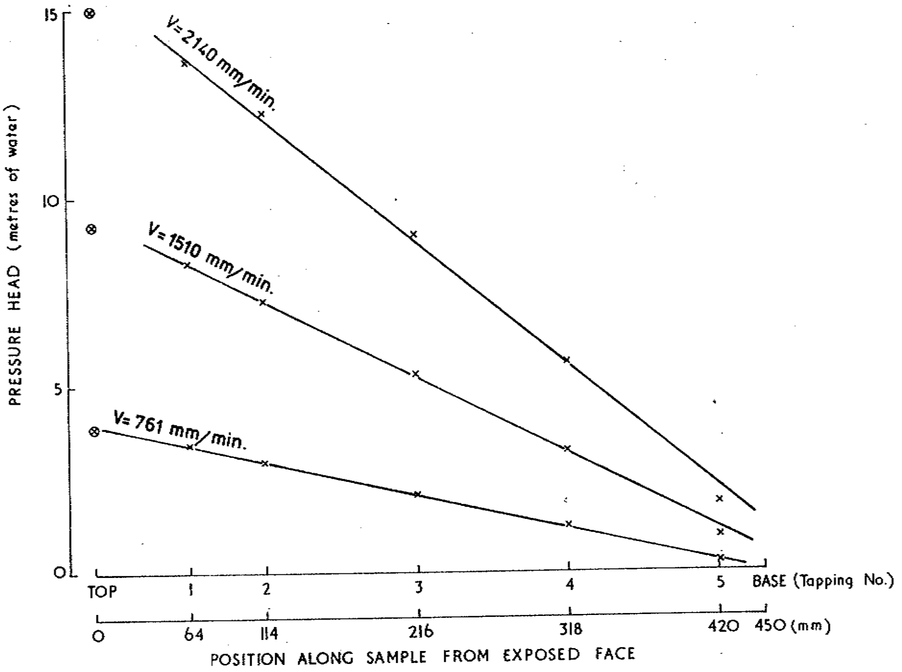


FIGURE 6·1(a) TEST 006. MATERIAL No. 2.
Pressure Distributions Before Exposure to Drilling Mud.

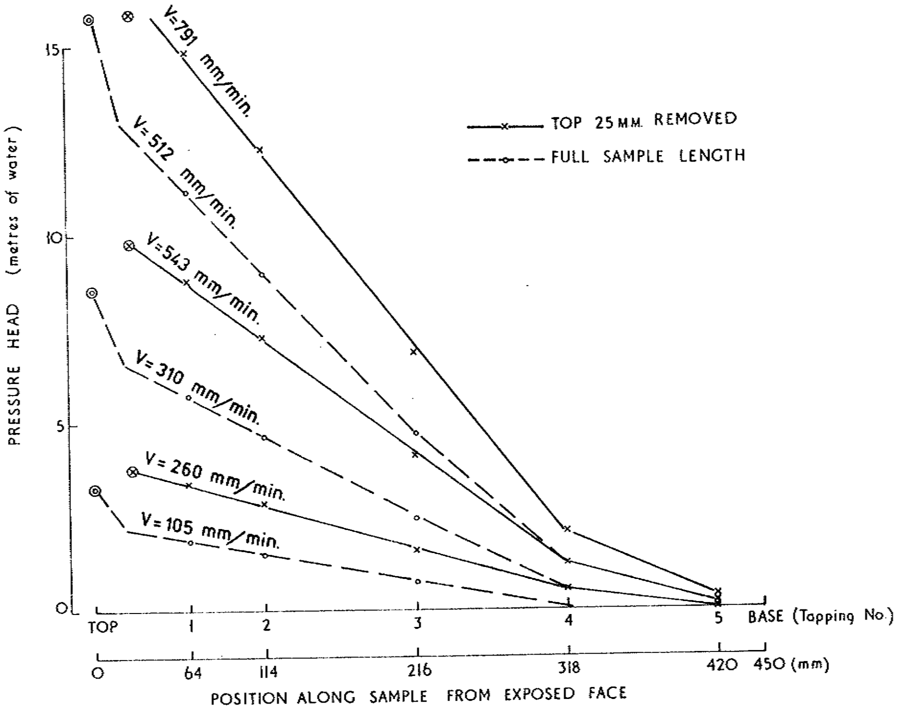


FIGURE 6·1(b) TEST 006. MATERIAL No. 2.
Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

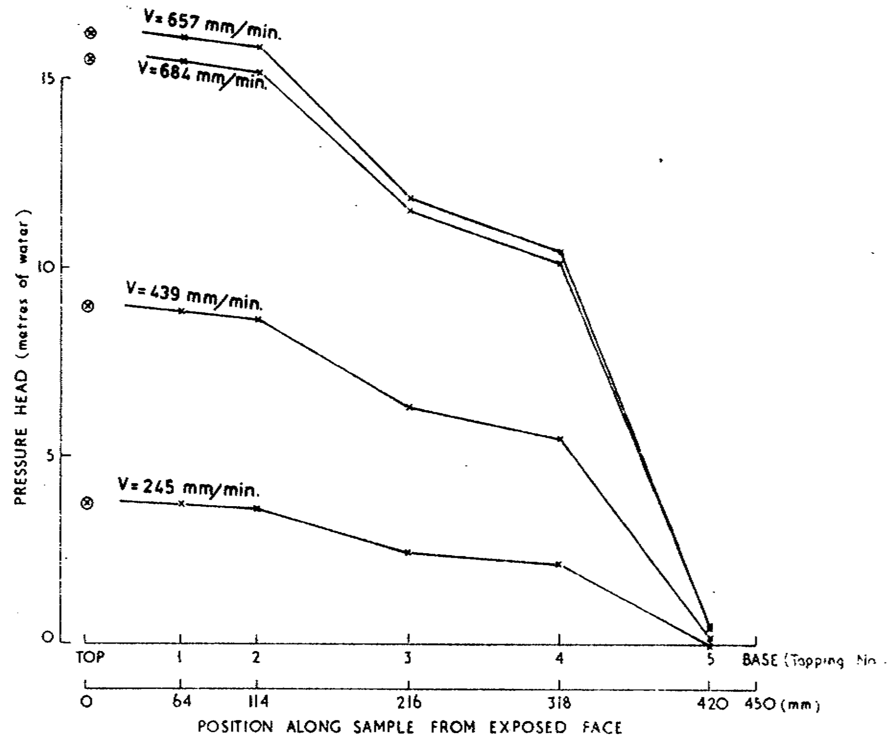


FIGURE 6·2(a) TEST 006. MATERIAL No. 6.

Pressure Distributions Before Exposure to Drilling Mud.

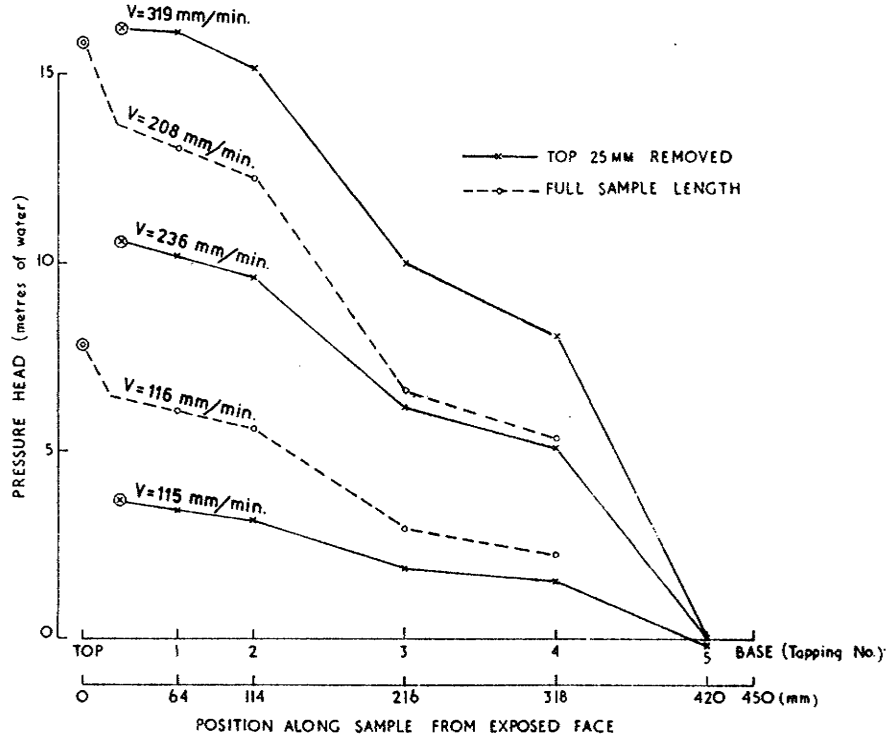


FIGURE 6·2(b) TEST 006. MATERIAL No. 6.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

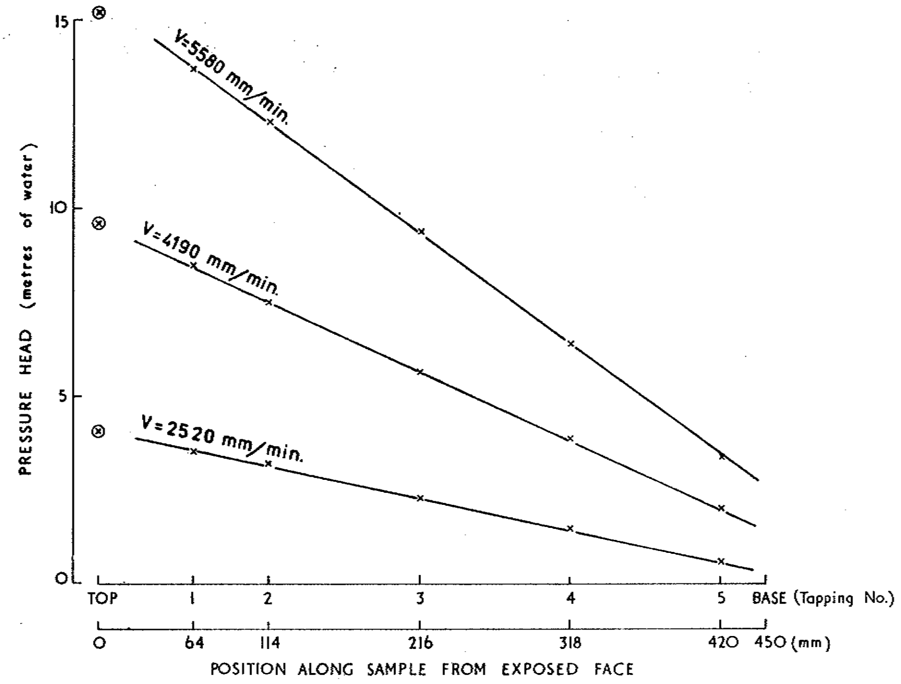


FIGURE 6·3(a) TEST 006. MATERIAL No. 3.

Pressure Distributions Before Exposure to Drilling Mud.

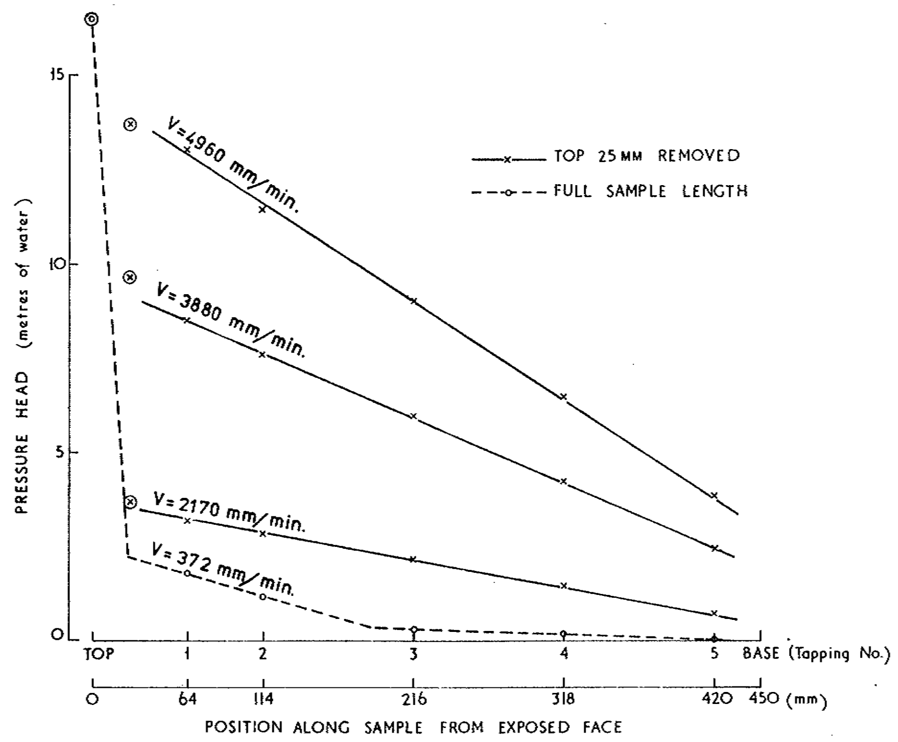


FIGURE 6·3(b) TEST 006. MATERIAL No. 3.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

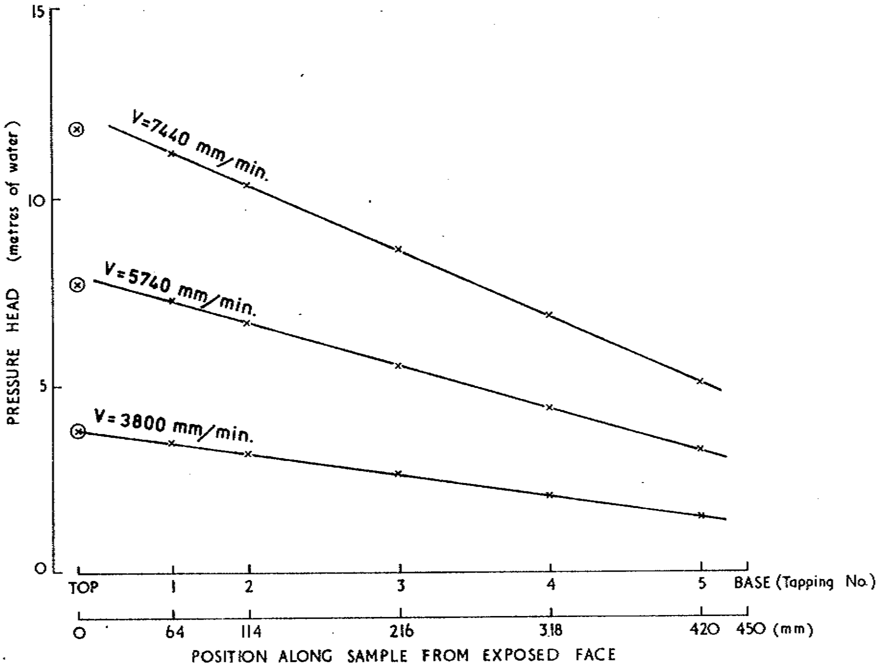


FIGURE 6.4(a) TEST 006. MATERIAL No. 4.

Pressure Distributions Before Exposure to Drilling Mud.

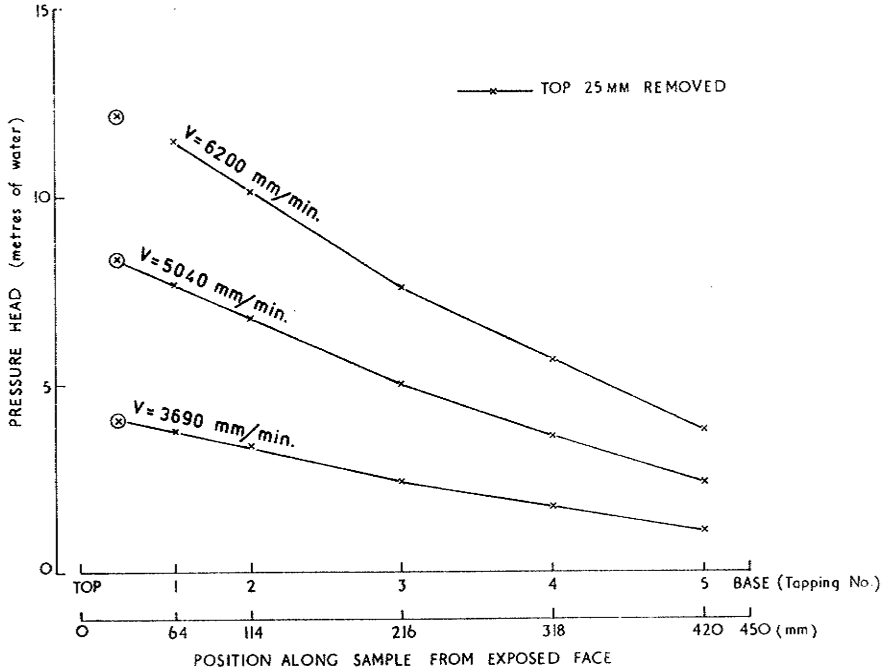
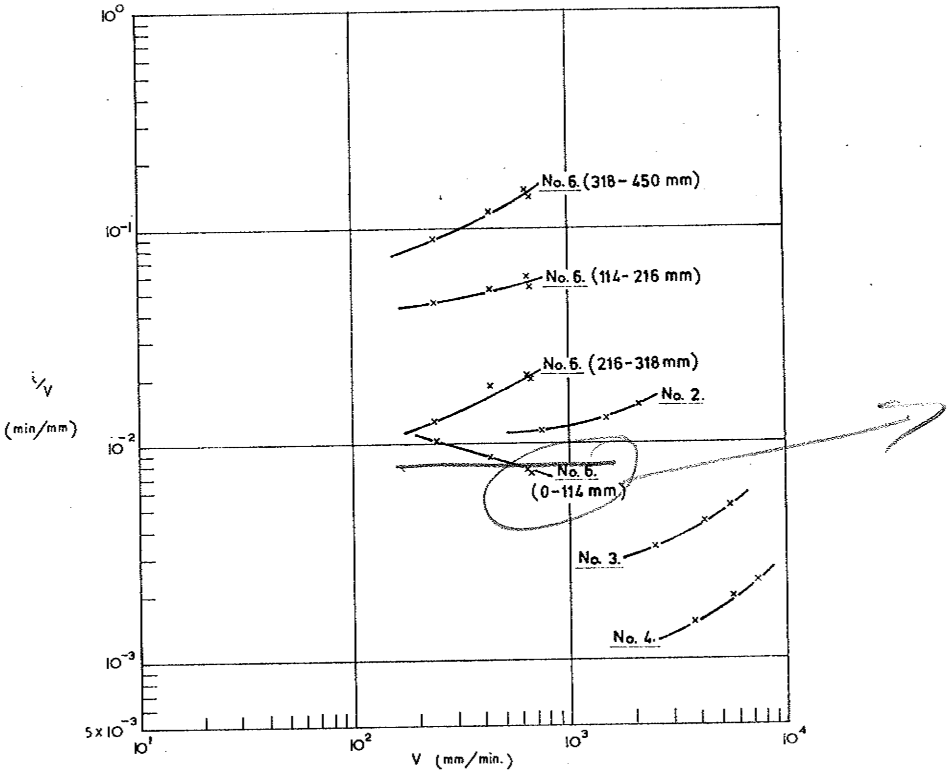
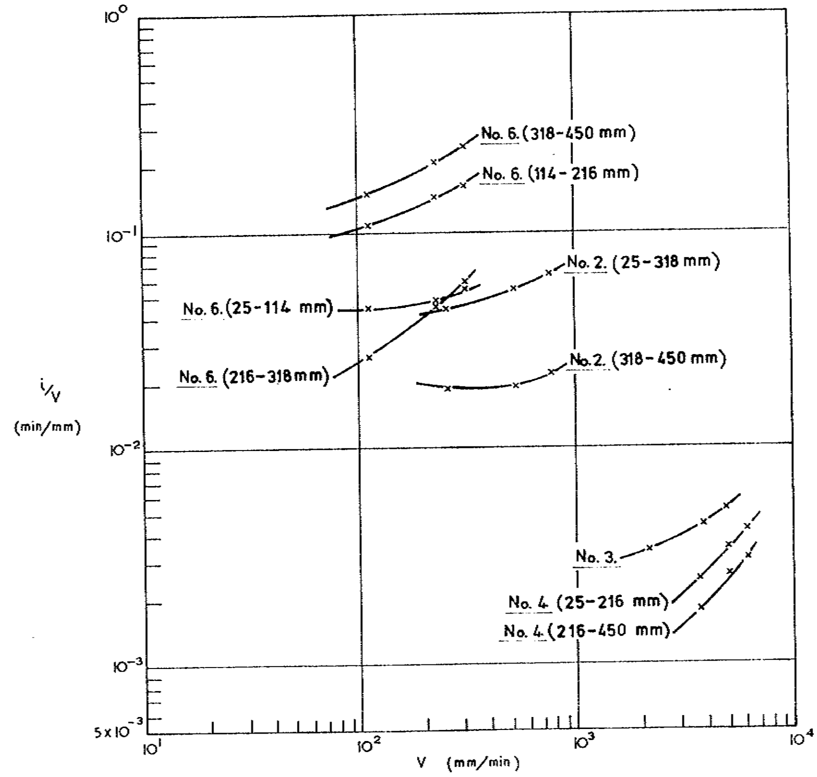


FIGURE 6.4(b) TEST 006. MATERIAL No. 4.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.



(a) Before Exposure to Drilling Mud



(b) After Exposure to Drilling Mud
Top 25 mm removed from sample

FIGURE 6·5 . TEST 006

HYDRAULIC FLOW PROPERTIES OF TEST MATERIALS (i/V versus V)

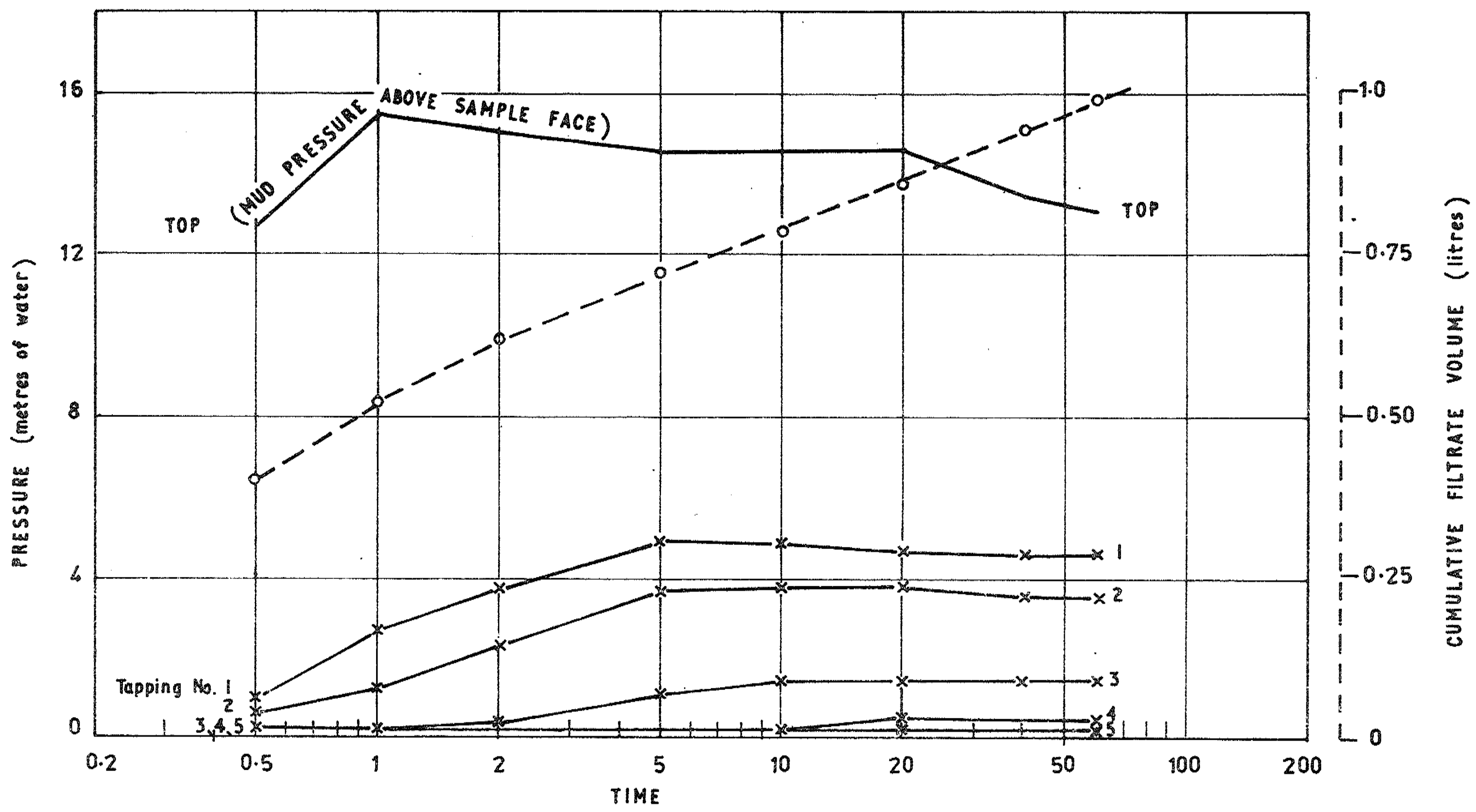


FIGURE 6·6: TEST 006 MATERIAL 2.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

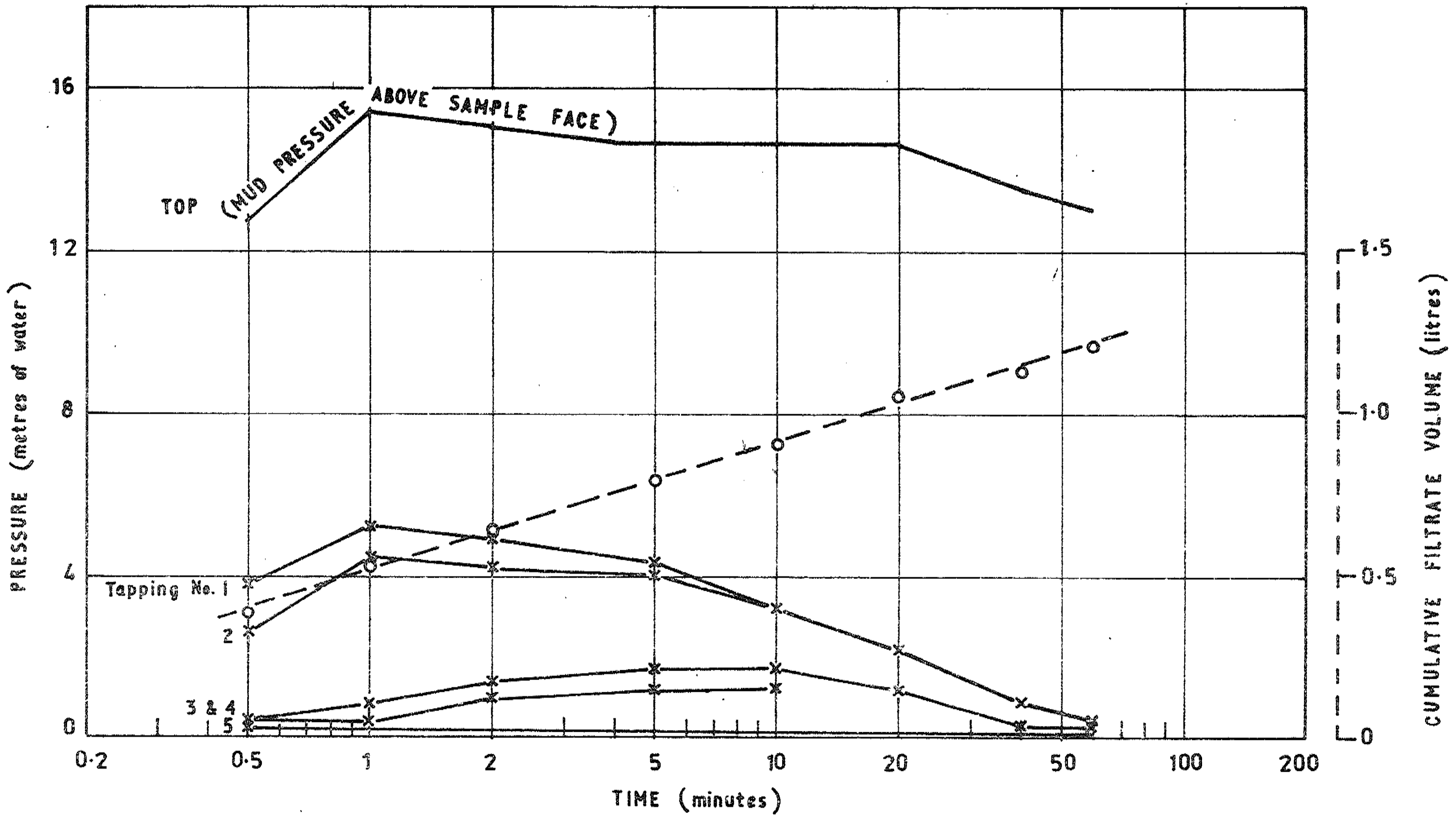


FIGURE 6·7 : TEST 006 MATERIAL 6.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

TABLE: 6.1 TEST: 006

Permeability testing of material samples.

Values of pressure (metres of water) as recorded at various positions along the sample for a measured flow of water through the sample.

Material	Flow Rate litres/min	Velocity mm/min	Tapping No.						
			Top		1	2	3	4	5
			Position along sample from datum (mm)						
			0	25	64	114	216	318	420
MATERIAL TESTS BEFORE EXPOSURE TO DRILLING MUD									
2	13.81	2140	14.95		13.67	12.29	9.01	5.61	1.83
	9.76	1510	9.19		8.26	7.25	5.30	3.22	0.95
	4.91	761	3.83		3.41	2.96	2.08	1.20	0.25
6	4.41	684	15.47		15.44	15.19	11.53	10.15	0.57
	4.24	657	16.07		16.07	15.82	11.85	10.46	0.44
	2.83	439	8.89		8.82	8.63	6.30	5.48	0.19
	1.58	245	3.60		3.72	3.59	2.46	2.15	-0.06
3	36.0	5580	15.16		13.67	12.29	9.39	6.37	3.34
	27.0	4190	9.50		8.45	7.50	5.67	3.85	1.96
	16.25	2520	4.05		3.53	3.15	2.27	1.45	0.57
4	48.0	7440	11.76		11.15	10.34	8.63	6.87	5.04
	37.0	5740	7.61		7.25	6.68	5.48	4.35	3.22
	24.5	3800	3.68		3.47	3.15	2.65	2.02	1.45
MATERIAL TESTS AFTER EXPOSURE TO DRILLING MUD Full Sample Length									
2	3.30	512	15.69		11.15	9.01	4.73	1.20	0.13
	2.00	310	8.51		5.74	4.67	2.46	0.57	0.07
	0.68	105	3.22		1.89	1.51	0.76	0.07	-0.06
6	1.34	208	15.84		13.04	12.23	6.62	5.30	
	0.75	116	7.76		6.11	5.61	2.96	2.27	
3	2.40	372	16.60		1.83	1.20	0.32	0.19	0.07
MATERIAL TESTS AFTER EXPOSURE TO DRILLING MUD Top 25 mm removed from sample									
2	5.10	791		15.84	14.81	12.23	6.87	2.08	0.32
	3.50	543		9.65	8.76	7.25	4.10	1.26	0.19
	1.68	260		3.68	3.34	2.84	1.58	0.51	0.00
6	2.05	319		15.99	16.07	15.19	9.96	8.07	0.07
	1.52	236		10.33	10.21	9.64	6.18	5.11	0.07
	0.74	115		3.53	3.41	3.15	1.89	1.58	-0.19
3	32.00	4960		14.56	13.04	11.47	9.01	6.49	3.85
	25.00	3880		9.65	8.51	7.56	5.99	4.22	2.40
	14.00	2170		3.75	3.22	2.84	2.15	1.45	0.70
4	40.00	6200		12.14	11.47	10.08	7.56	5.61	3.72
	32.50	5040		8.29	7.63	6.74	4.98	3.59	2.33
	23.80	3690		3.90	3.78	3.34	2.40	1.70	1.07

TABLE 6.2 TEST 006

Sample behaviour during time of exposure to drilling mud.

Material	Time (minutes)	Filtrate Volume (litres)	Pressure (metres of water)					
			Tapping No.					
			Top	1	2	3	4	5
			Position along sample from datum (mm)					
			0	64	114	216	318	420
2	½	.40	12.68	.95	.44	.19	.19	.19
	1	.52	15.47	2.71	1.20	.26	.19	.19
	2	.62	14.94	3.72	2.33	.32	.19	.19
	5	.72	14.57	4.85	3.59	1.07	.19	.19
	10	.78	14.57	4.73	3.72	1.45	.19	.19
	20	.86	14.57	4.60	3.72	1.45	.44	.19
	40	.94	13.43	4.54	3.53	1.45	.44	.26
	60	.99	13.05	4.48	3.53	1.45	.44	.32
6	½	.38	12.68	3.85	2.59	.32	.32	.19
	1	.52	15.47	5.23	4.35	.82	.32	.19
	2	.64	14.94	4.85	4.22	1.45	.95	.19
	5	.79	14.57	4.35	3.97	1.70	1.20	.19
	10	.90	14.57	3.22	3.22	1.70	1.20	.26
	20	1.05	14.57	2.21		1.20		.19
	40	1.12	13.43	0.82		0.32		.13
	60	1.20	13.05	0.44	0.44	0.32		.13
3	½	.2	12.68	.19	.19	.19	.19	.19
	1	.2	15.47	.32	.32	.19	.19	.19
	20	.2	14.57	.19	.32	.19	.19	.19
	60	.2	13.05	.32	.19	.07	.07	.07
4	½	1.0	12.68	.82	.70	.44	.19	.19
	1	1.0	15.47	.95	.82	.57	.44	.19
	2	1.0	14.94	1.20	.95	.82	.32	.19
	20	1.0	14.57	.95	.44	.57	.32	.19
	60	1.0	13.05	.82	.19	.57	.44	.07

V7 Test 007: Results and Observations

A mud was prepared which contained 6½% by weight Aquagel and 6% by weight of the sand shown in Figure 1.1.

Suggestions had been made by members of the AWRC committee to test a lime contaminated mud which would build heavy but low efficiency wall cakes.

Samples of materials 2, 3, 4, 6 were prepared and original permeabilities measured.

Thirty minutes prior to starting the test approximately 1 cupful of hydrated lime was added to the mud which was at that time being circulated via the by-pass line at test pressure and velocity. Within 15 minutes the mud had thickened to the extent that at the present valve settings the pump began to labour noticeably. All valves within the circulating system were fully opened and the flow was maintained. The mud continued to thicken and within another 5 minutes the pump laboured heavily and the discharge flow ceased. The pump now ran smoothly, but dry since no mud was being drawn from the mud bin into the pump inlet.

All lines were heavily blocked by the mud which appeared to be "a two week old porridge".

At this stage the test had to be abandoned and the circulation system disassembled and cleaned which was quite a difficult task.

It is the author's opinion that all test materials would have been instantly sealed by a large external cake build-up above the sample surface if it had been possible to circulate such a thick mud.

No estimate of possible permanent damage could be even guessed.

V8 Test 008 Results and Observations

The mud was made up as approximately 0.9% (9 lbs/100 gallons) by weight Hydropol (old stock). The mud was circulated for $1\frac{1}{2}$ hours prior to starting the test. The mud properties were tested at various times both before and during the exposure of the sample materials to the mud. The results of such tests were as follows:-

Time mins.	Temp. °C	Marsh Funnel Viscosity secs.	API Filter Press ($\frac{1}{2}$ area) Initial Spurt (V_s+V_x) cc	Corrected Volume (V_c) cc	Plastic Viscosity cps	Yield Point lb/100ft^2
-90	20	$35\frac{1}{2}$	17.8	5.8	6.2	5
+50	19	37	20.2	4.8	6.0	5
+100	17	$35\frac{1}{2}$				
+140	17	35	10.0	5.2	6.0	5

The specific gravity of the mud was 1.00 (with the accuracy of the mud balance no difference between the mud and water was noticeable). In all API filter press tests the thickness of the filter cake was negligible.

During the exposure time of $2\frac{1}{2}$ hours, both the mud flow pressure and velocity varied considerably about the target values of 10 psi (7 metres of water) and 120 ft/min respectively (Figure 8.1).

After 150 minutes of pressurized mud flow the pump was turned off and the test apparatus was isolated. The pressure was relieved and the mud was left to stand (static flow condition) above the sample for 19 hours.

All mud was drained from above the samples and water was gently washed through the test cell for 20 minutes to clean all mud from the apparatus.

The apparatus was filled with water and each material flushed through under applied pressures up to 20 psi until no further improvement in flow could be obtained.

Each sample was retested for material permeability.

Romud P.B.D. in the recommended concentration of 0.75 lb/100 gallons was added to the test apparatus and left to stand above the samples for 66 hours.

Fluid was flushed through each material until the pH change indicated that P.B.D. solution was present throughout the sample length. Each sample was left as such for 30 minutes before further flushing was carried out to achieve optimum sample rehabilitation.

The samples were then retested for permeability to estimate the extent of permanent damage caused by exposure to the mud system.

The samples were left covered with water for 16 hours before being finally removed and inspected.

Material 1

Porosity = 38.6%

(original) Linear K_O = 22 mm/min.
(Table 8.1, Figures 8.2a, 8.6)

See Table 8.2 and Figure 8.7. Within ½ minute of exposure a seal formed somewhere in the top 64 mm of the sample which accounted for a pressure drop from 6.65 metres at the exposed face to 1.33 metres of water head at tapping 1. This seal gradually improved its effectiveness with time of exposure until after 150 minutes the pressure drop between the sample face and tapping 1 was from 6. 96 to 0.82 metres of water.

However, the seal was not as effective as those formed in tests using bentonite muds and although the mud filtrate loss rate decreased in time to a value of approximately 2 cc/min, it did continue. (Test 002 - 6½% Aquagel - pressure differential = 20 psi - mud velocity = 120 ft/min - an effective seal formed in the top 10 mm of this material within 1 minute of exposure - the seal prevented any mud filtrate loss beyond .235 litres and thus limited filtrate penetration to a depth of 90 mm into the material).

The mud filtrate would have penetrated the entire sample length after 20 minutes when the collected filtrate volume was 1.06 litres.

The total volume of filtrate collected was 1.68 litres.

When the sample was flushed with water, a small but noticeable improvement was achieved.

The results of permeability testing after water flushing alone are given in Table 8.1 and Figures 8.2b, 8.6.

The seal above tapping 1 was still apparent (Figure 8.2b) although its effectiveness had been reduced by the water flushing. The remainder of the material appeared to be homogeneous and exhibited linear flow behaviour. An estimate of permeability (from Figure 8.6) of 17.2 mm/min. for the material beyond tapping 1 indicates a reduction of 23% in permeability.

After P.B.D. treatment and further flushing the material was again tested for permeability. (Table 8.1, Figures 8.2b, 8.6). The seal above tapping 1 had been completely broken down by the P.B.D. solution and the entire sample material appeared to be homogeneous. However, the permeability of the entire sample (as estimated from Figures 8.2b, 8.6) was the same as that exhibited by the material beyond tapping 1 after flushing with water along.

The P.B.D. had been effective in breaking down the developed sealing layer where water flushing alone had only limited success. However, beyond the seal there had been permanent damage done to the material resulting in a permeability reduction of 23%. The P.B.D. treatment had no effect in reducing the extent of this permanent damage.

When the sample was finally removed and inspected a 1 mm thick layer of material of different colour to the remainder of the sample was evident at the face of the sample. This layer in its present state was quite permeable. It is the author's opinion that the visual material colour change noted, clearly indicates the developed seal (somewhere above tapping 1) as being a very thin 1 mm thick layer at the face of the sample.

Material 2

Porosity = 39.4%

(original) Non-linear K_O = $1/a$ = 96 mm/min, b/a^2 = .020
(Table 8.1, Figures 8.3a, 8.6)

See Table 8.2 and Figure 8.8. A relatively minor degree of sealing had occurred somewhere in the top 64 mm of the sample within the first $\frac{1}{2}$ minute of exposure. This was indicated by the pressure drop from 6.65 metres at the exposed face to 2.96 metres of water at tapping 1. The effectiveness of this seal gradually improved with time of exposure until after 150 minutes the pressure drop between the sample face and tapping 1 was 6 metres of water.

The mud filtrate flow was reduced from 450 cc/min. at $\frac{1}{2}$ minute to 10 cc/min. at 150 minutes. Mud filtrate would have penetrated the entire sample length after only 3 minutes of exposure when the collected filtrate volume was 1.14 litres. Although the mud filtrate loss rate decreased in time, the flow rate at the end of the test was still substantial and a total volume of 5.2 litres was collected.

The seal developed during this test was markedly less effective than those seals formed by bentonite muds. In tests 002, 003 and 004 a $6\frac{1}{2}\%$ Aquagel mud formed effective seals in the top 10 mm of this material within $\frac{1}{2}$ minute of exposure. The seals so developed in tests 002, 003 and 004 prevented any further loss of mud filtrate beyond the $\frac{1}{2}$ minute values of 0.19, 0.56 and 0.92 litres for the respective tests.

When the sample was flushed with water, a significant improvement was readily achieved.

The results of permeability testing after water flushing alone are given in Table 8.1 and Figures 8.3b, 8.6. The effectiveness of the sealing layer above tapping 1 had been virtually eliminated by water flushing alone, (Figure 8.3b). However, over the remainder of the sample there was an overall reduction in material permeability which appeared to be graded with distance from the exposed face as follows:-

(exposed) 64-114 mm Non-linear K_e = 1/a = 45 mm/min, b/a^2 = .007
114-318 mm Non-linear K_e = 1/a = 61 mm/min, b/a^2 = .015
318-450 mm Non-linear K_e = 1/a = 74 mm/min, b/a^2 = .018
(Table 8.1, Figures 8.3b, 8.6)

These values indicate permeability reductions of 53%, 36% and 23% for the 64-114, 114-318 and 318-450 mm layers respectively.

After P.B.D. treatment and further flushing, the material was again tested for permeability. The seal above tapping 1 had been completely broken down by this time and the entire sample material appeared to be homogeneous.

(exposed) Non-linear K_e = 1/a = 36 mm/min, b/a^2 = .011
(Table 8.1, Figures 8.3b, 8.6)

This indicates an overall permeability reduction of 62% for the entire sample.

The P.B.D. treatment had removed the final marginal traces of the sealing layer above tapping 1 which water flushing alone had previously been unable to do. However, the material permeability after P.B.D. treatment was lower than the previous least permeable 64-114 mm layer after water flushing. No logical explanation for this phenomenon can be made by the author.

When the sample was finally removed and inspected, remnants of a 1 mm thick layer at the face of the sample were evident. It is the author's opinion that the formation of this thin sealing layer at the exposed face of the sample caused the reduction inloss of mud filtrate from the sample with time of exposure.

Material 3

Porosity = 39.4%

(original) Non-linear K_o = 1/a = 560 mm/min, b/a^2 = .18
(Table 8.1, Figures 8.4a, 8.6)

See Table 8.2 and Figure 8.9. With time of exposure, there was a steady decrease in permeability of some portion of the sample between the exposed face and tapping 1. This was indicated by the gradual increase in the pressure difference between the face and tapping 1. The formation of a stable layer of reduced permeability (most likely to be at the sample face) appeared to be complete after 40 minutes of exposure. After 40 minutes there was negligible change in the pressure heads at the five tappings throughout the sample length.

Whole mud flowed freely from the sample for most of this test. The flow of mud from the sample had been reduced from 5 litres/min. at $\frac{1}{2}$ minute to 0.33 litres/min. at 40 minutes. Further decreases continued at a far lower rate until after 150 minutes the loss of mud filtrate from the sample was 0.12 litres/min. and a total volume of 52 litres had passed through the sample.

The inability of this hydropol mud to eliminate filtrate loss to the material was in sharp contrast to the completely effective seal developed by a $6\frac{1}{2}$% Aquagel mud in Test 003. In Test 003 a seal formed within 10 minutes which prevented any further loss of mud filtrate beyond 15 litres.

When the sample was flushed with water, a significant improvement was readily achieved.

The results of permeability testing after water flushing alone are now given;

(exposed) Non-linear K_e = 1/a = 460 mm/min, b/a^2 = .47
(Table 8.1, Figures 8.4b, 8.6)

A marked rehabilitation of the low permeability layer which developed above tapping 1 during mud exposure had been achieved by water flushing alone. However, the entire sample had apparently suffered a reduction in permeability.

After P.B.D. treatment and further flushing the material was again tested for permeability.

(exposed) 64-216 mm Non-linear K_e = 1/a = 575 mm/min, b/a^2 =.39
216-450 mm Non-linear K_e = 1/a = 500 mm/min, b/a^2 =.38
Table 8.1, Figures 8.4b, 8.6)

There was still evidence of a minor permeability reduction above tapping 1. The P.B.D. treatment has significantly aided in the permeability recovery of the sample.

For materials with $b/a^2 > 0.1$ the reliability of extrapolating non-linear equations ($i = aV+bV^2$) as determined from only 3 points to a value of permeability K = 1/a is very low. In such cases, estimates of damage may be more reliably evaluated by comparing the hydraulic gradients necessary to achieve specified flow velocities. This was done for both the water flushed and subsequently P.B.D. treated permeability tests of the exposed sample for a velocity of 3000 mm/min. (Figure 8.6). Permanent damage had been done to the material by exposure to the mud flow. Water flushing alone was limited in its ability to rehabilitate the material - resultant overall permeability reduction of 65%. The P.B.D. treatment further aided in recovery of the sample, but was also limited. After P.B.D. treatment and final flushing reductions in permeability of 35% and 45% were still present in 64-216 mm and 216-450 mm portions of the sample.

When the sample was finally removed and inspected the entire sample appeared homogeneous. There was no visual evidence of any layer of lower permeability between the sample face and tapping 1.

Material 6

Porosity = 31.4%

0-64 mm More permeable than 64-114 mm
(original) 64-114 mm Not very reliable $K_o > 120$ mm/min.
114-216 mm Linear $K_o = 40$ mm/min.
216-318 mm Non-linear $K_o = 1/a = 27$ mm/min,
$b/a^2 = .017$
318-450 mm Non-linear $K_o = 1/a = 140$ mm/min,
$b/a^2 = .61$
(Table 8.1, Figures 8.5a, 8.6)

As can be seen the sample had various layers of differing permeability throughout its length. The permeability was relatively high between 0 and 114 mm, low between 114-318 mm and again high for the remainder of the sample.

See Table 8.2 and Figure 8.10. An effective sealing layer developed within $\frac{1}{2}$ minute at some location between tappings 2 and 3. The seal at this time accounted for a pressure head drop between tappings 2 and 3 of 5.35 metres of water. The seal marginally improved in effectiveness up to an exposure time of 5 minutes, beyond which time it accounted for more than 95% of the total head loss across the entire sample length. The head losses across the various other layers of the material were negligible.

It was significant that the seal developed in the first low permeability layer of the material encountered (114-216 mm, $K_o = 40$mm/min).

The developed seal did not fully stem the flow of mud filtrate from the sample. The rate of loss of mud filtrate did, however, decline to such an extent that beyond 30 minutes it was never above 2cc/min.

The mud filtrate would have penetrated the entire sample length after 30 minutes when the collected filtrate volume was 0.91 litres.

When attempts were made to flush the sample with water under applied pressures up to 25 psi only minor success was possible due to the continued effectiveness of the sealing layer between tappings 2 and 3.

The results of permeability testing after water flushing alone are now given:

(exposed) 0-114 mm Too difficult to estimate permeability due to very low pressure drop
114-216 mm Linear $K_e = 1.1$ mm/min.
216-318 mm Non-linear $K_e = 1/a = 6.6$ mm/min, $b/a^2 = .007$
318-450 mm Non-linear $K_e = 1/a = 43$ mm/min, $b/a^2 = .28$
(Table 8.1, Figure 8.5b, 8.6)

As can be seen the water flushing has not been very effective in rehabilitating the sample. The indicated reductions in permeability for the 114-216, 216-318 and 318-450 mm layers are 97%, 75% and 70% respectively.

After P.B.D. treatment, water flushing of the sample was continued at an improved rate and then the sample retested for permeability.

(exposed) 0-114 mm Too difficult to estimate permeability due to very low pressure drop
114-216 mm Linear $K_e = 4.8$ mm/min.
216-318 mm Non-linear $K_e = 1/a = 11$ mm/min, $b/a^2 = .027$
318-450 mm Non-linear $K_e = 1/a = 32$ mm/min, $b/a^2 = .11$

The P.B.D. treatment produced an improvement over the water flushing alone. There had still been considerable permanent damage done to the sample resulting in permeability reductions of 88%, 58% and 78% for the 114-216, 216-318, and 318-450 mm layers respectively.

The P.B.D. treatment had only significantly improved the 114-216 and 216-318 mm layers of the sample. These were the original low permeability layers of the sample. The 318-450 mm layer was originally a high permeability layer of the sample and P.B.D. treatment produced no improvement over rehabilitation possible by water flushing alone.

If higher flushing velocities were possible the sample may have cleaned up considerably more than it did. However, the sealing layer between 114 mm and 216 mm was far enough removed from the sample face to be extremely difficult to erode. Perhaps continued extensive P.B.D. treatment would have reduced the seal's effectiveness.

The sample was finally removed from the apparatus and inspected. Visual banding of the material was evident throughout the entire length. This banding was present when the original sample was prepared. Apparent bands of finer material were regularly 20-30 mm thick. When permeabilities were estimated for the sample, layers were assumed homogeneous between pressure tappings. If, however, the major portion of the pressure drop between two tappings was caused by a 20 mm layer of finer material then the permeability of such a thin layer would be approximately $\frac{1}{4}$ that of the indicated permeability taken over the full distance between the two tappings. Bearing this in mind, it is quite possible that thin layers of material having permeabilities less than 10 mm/min may have existed in the original sample.

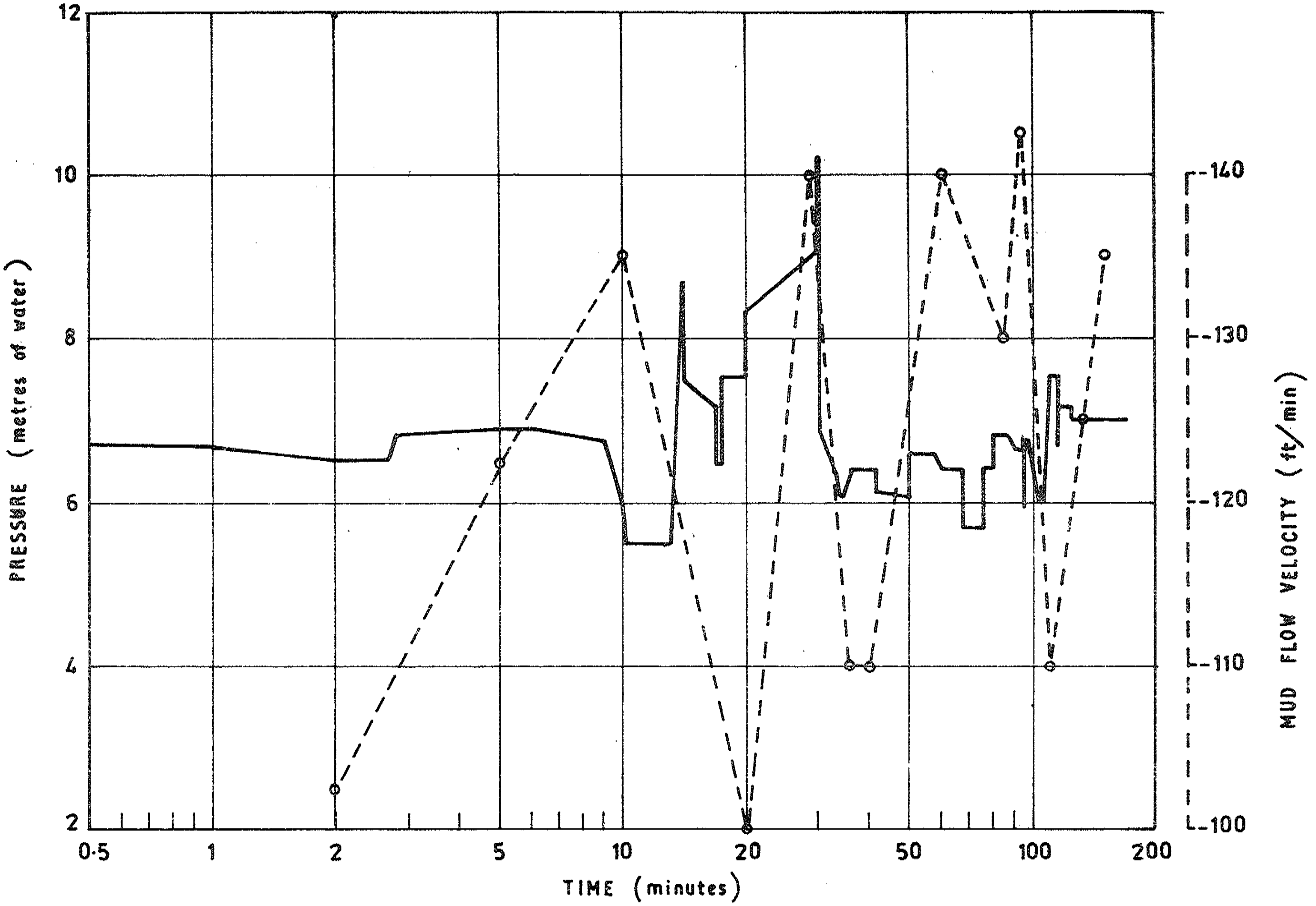


FIGURE 8·1 TEST 008

MUD FLOW PRESSURE AND VELOCITY VARIATIONS DURING TIME OF EXPOSURE

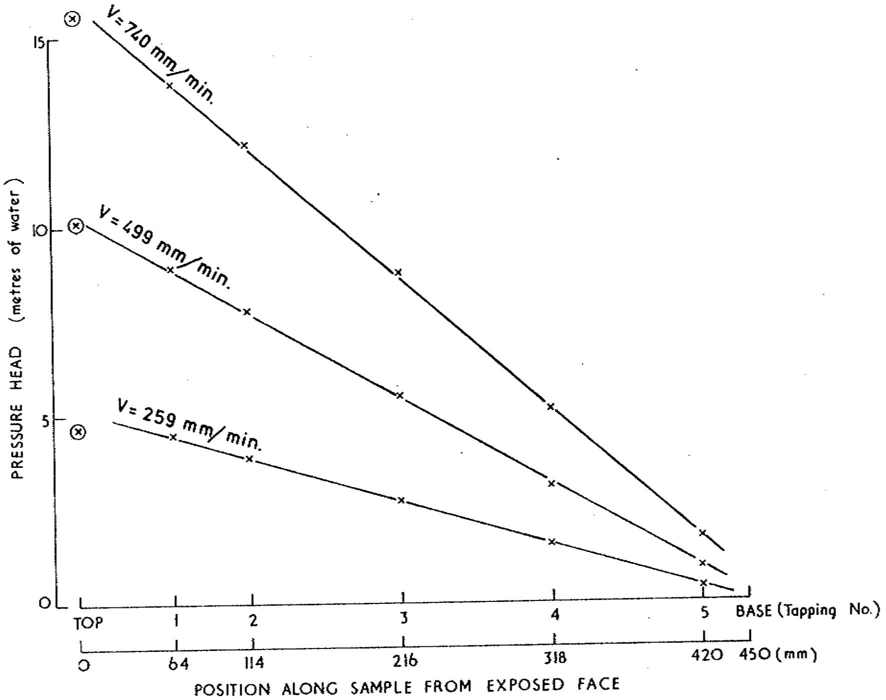


FIGURE 8·2(a) TEST 008 MATERIAL No.1.

Pressure Distributions Before Exposure to Drilling Mud.

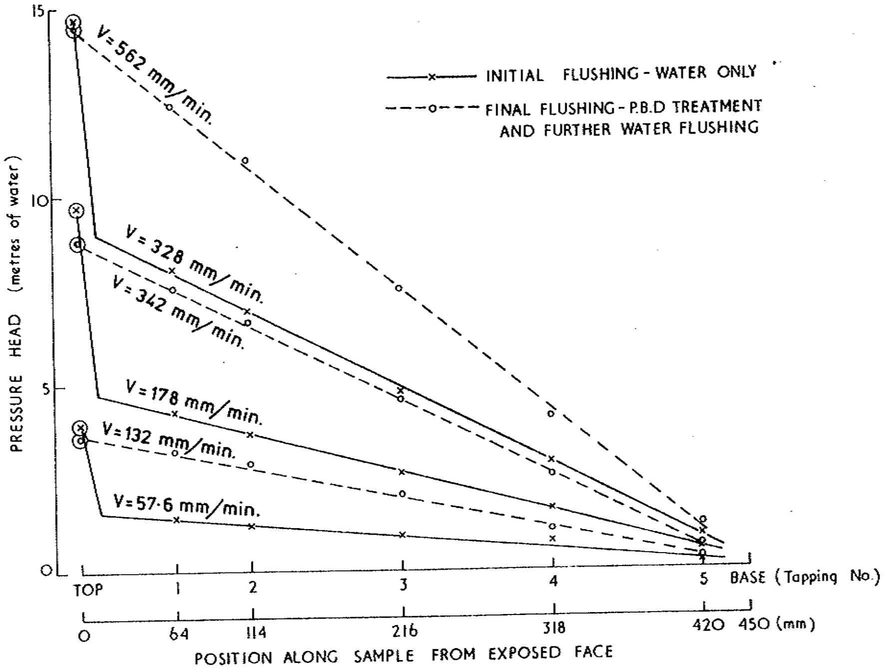


FIGURE 8·2(b) TEST 008 MATERIAL No.1.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

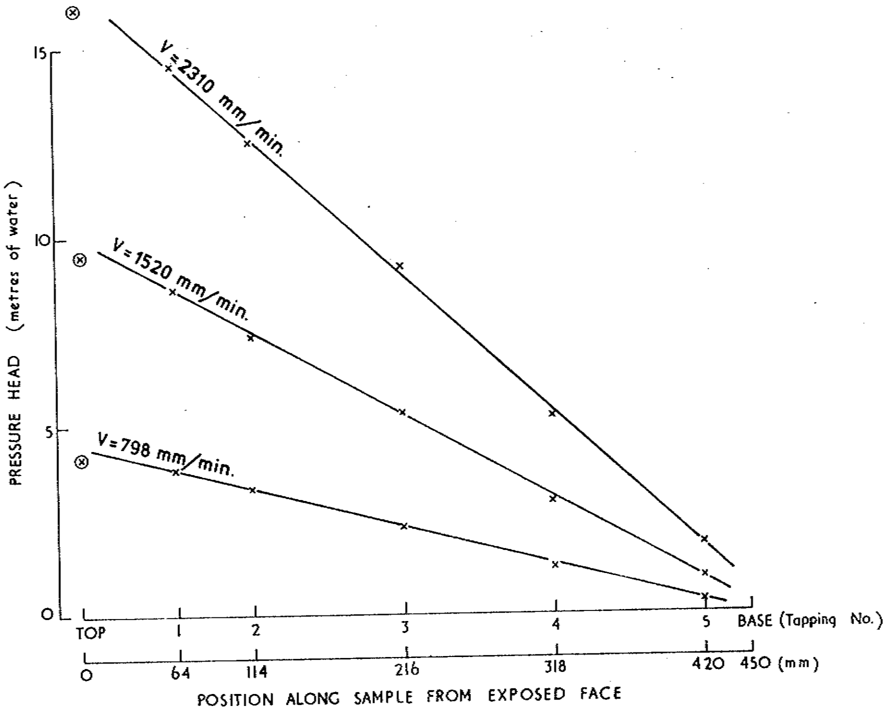


FIGURE 8·3 (a) TEST 008 MATERIAL No. 2.

Pressure Distributions Before Exposure to Drilling Mud.

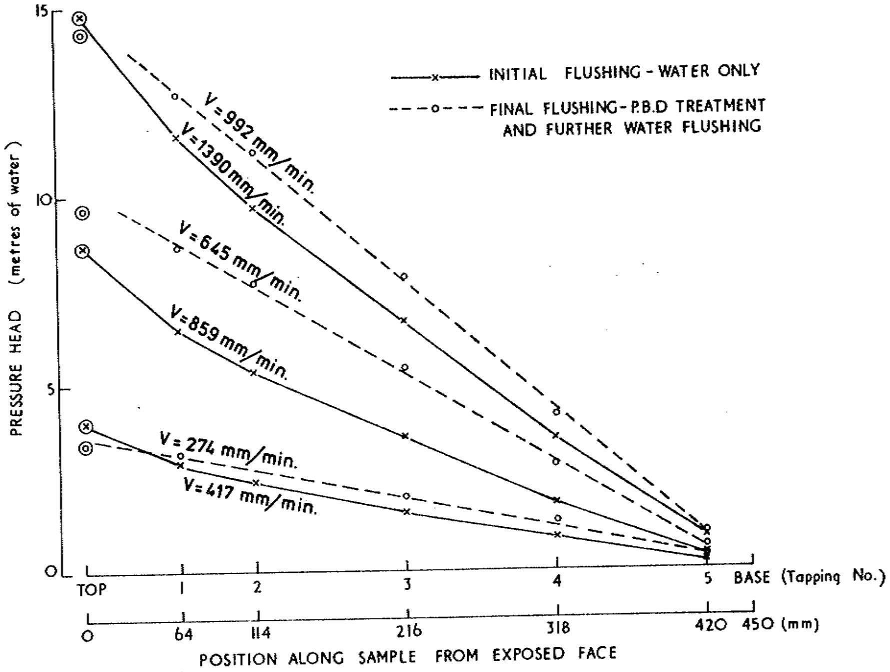


FIGURE 8·3 (b) TEST 008 MATERIAL No. 2.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

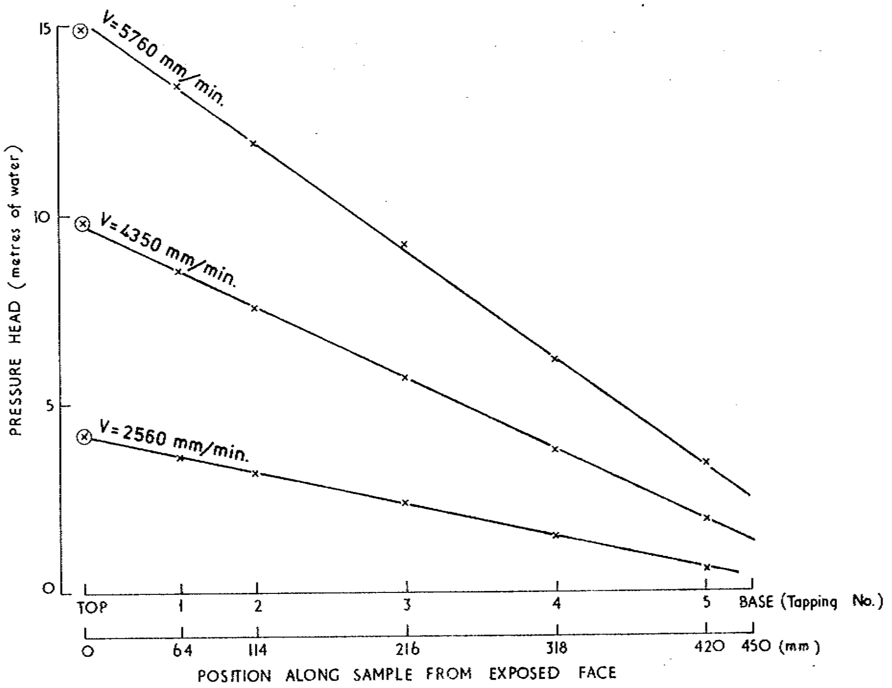


FIGURE 8·4(a) TEST 008 MATERIAL No. 3.

Pressure Distributions Before Exposure to Drilling Mud.

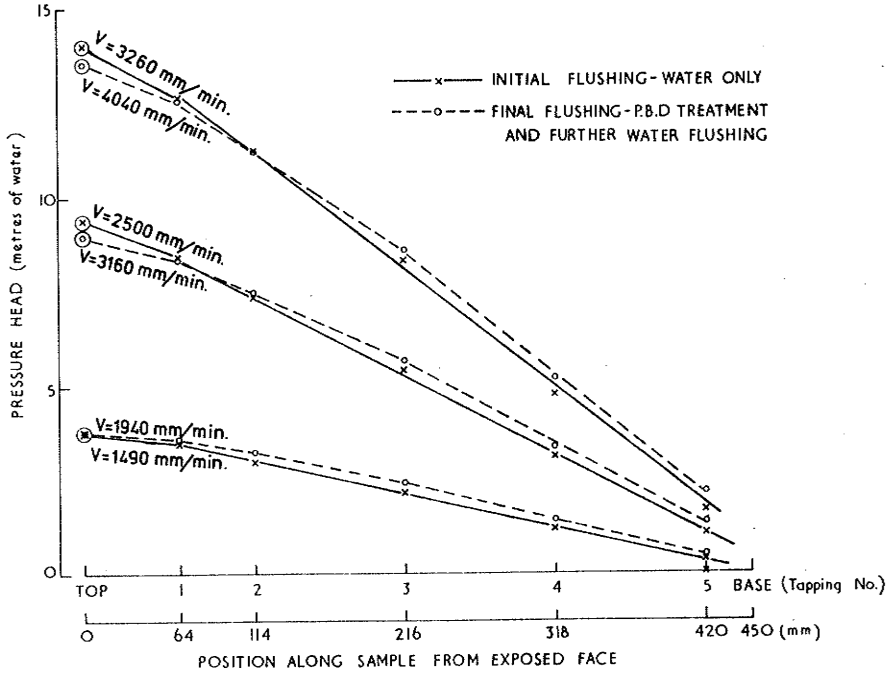


FIGURE 8·4(b) TEST 008 MATERIAL No. 3.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

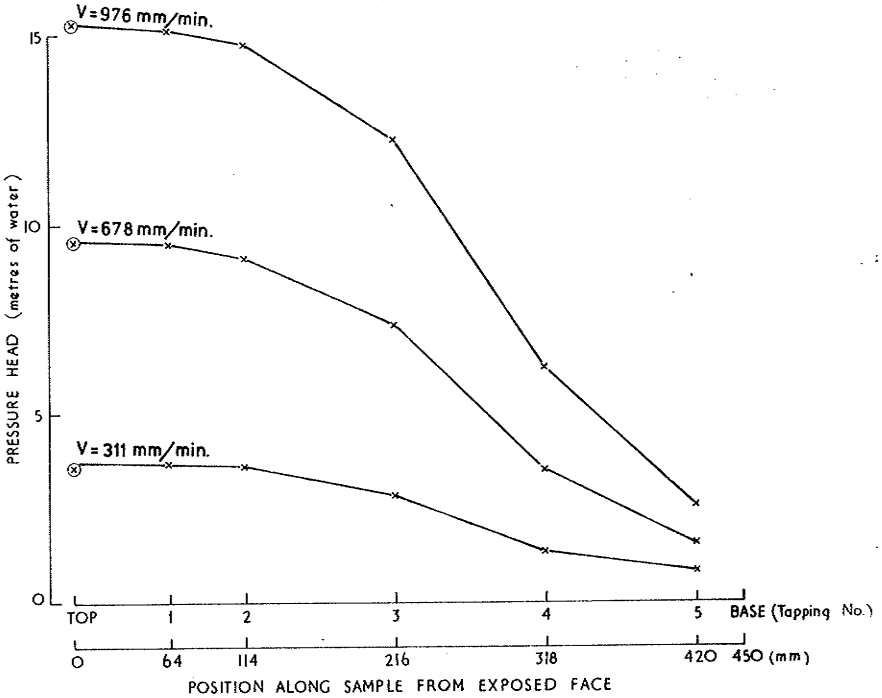


FIGURE 8·5(a) TEST 008 MATERIAL No. 6

Pressure Distributions Before Exposure to Drilling Mud.

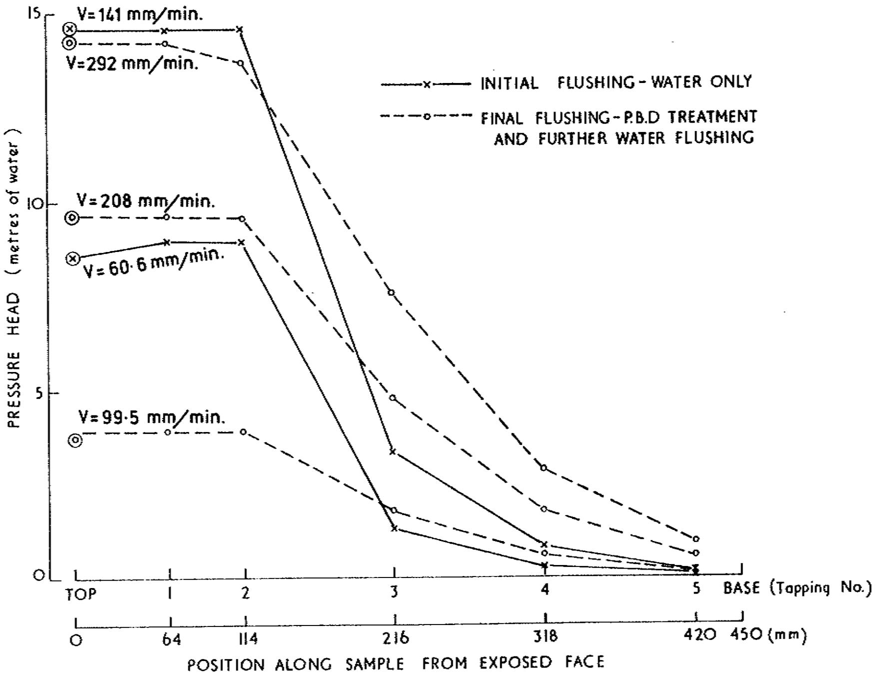
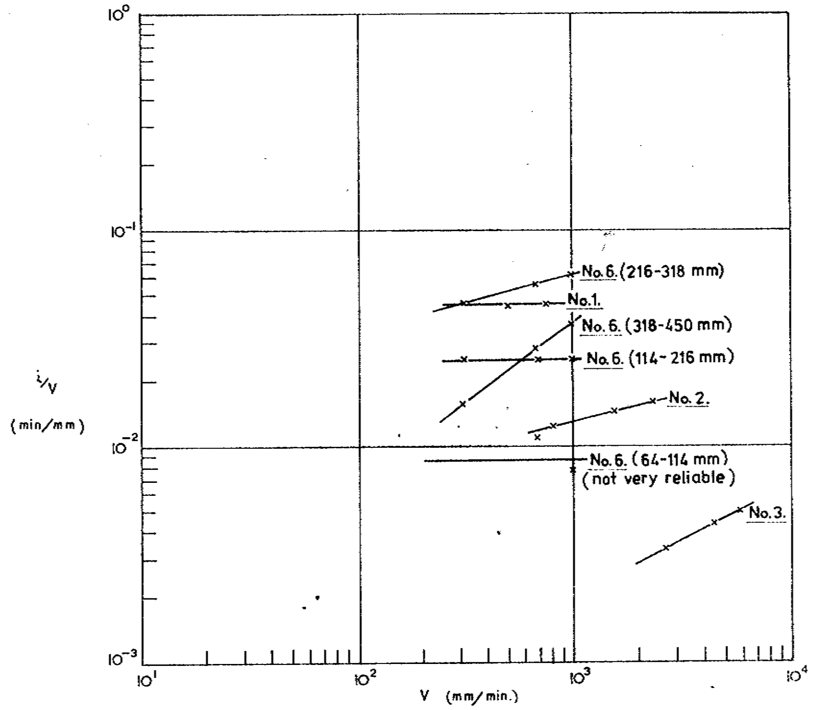
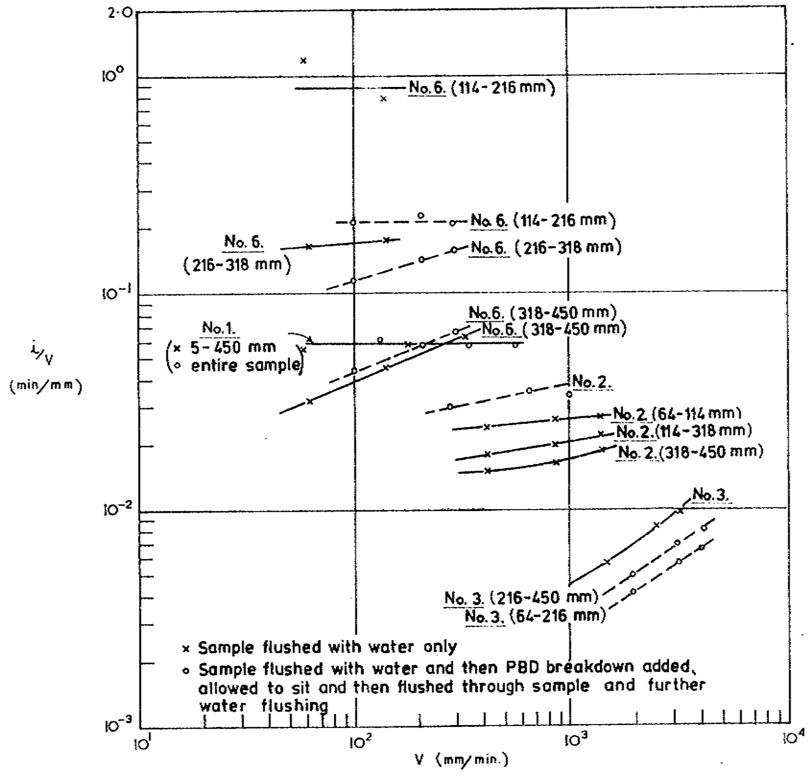


FIGURE 8·5(b) TEST 008 MATERIAL No. 6.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.



(a) Before Exposure to Drilling Mud



(b) After Exposure to Drilling Mud

FIGURE 8·6 TEST 008

HYDRAULIC FLOW PROPERTIES OF TEST MATERIALS (i/V versus V)

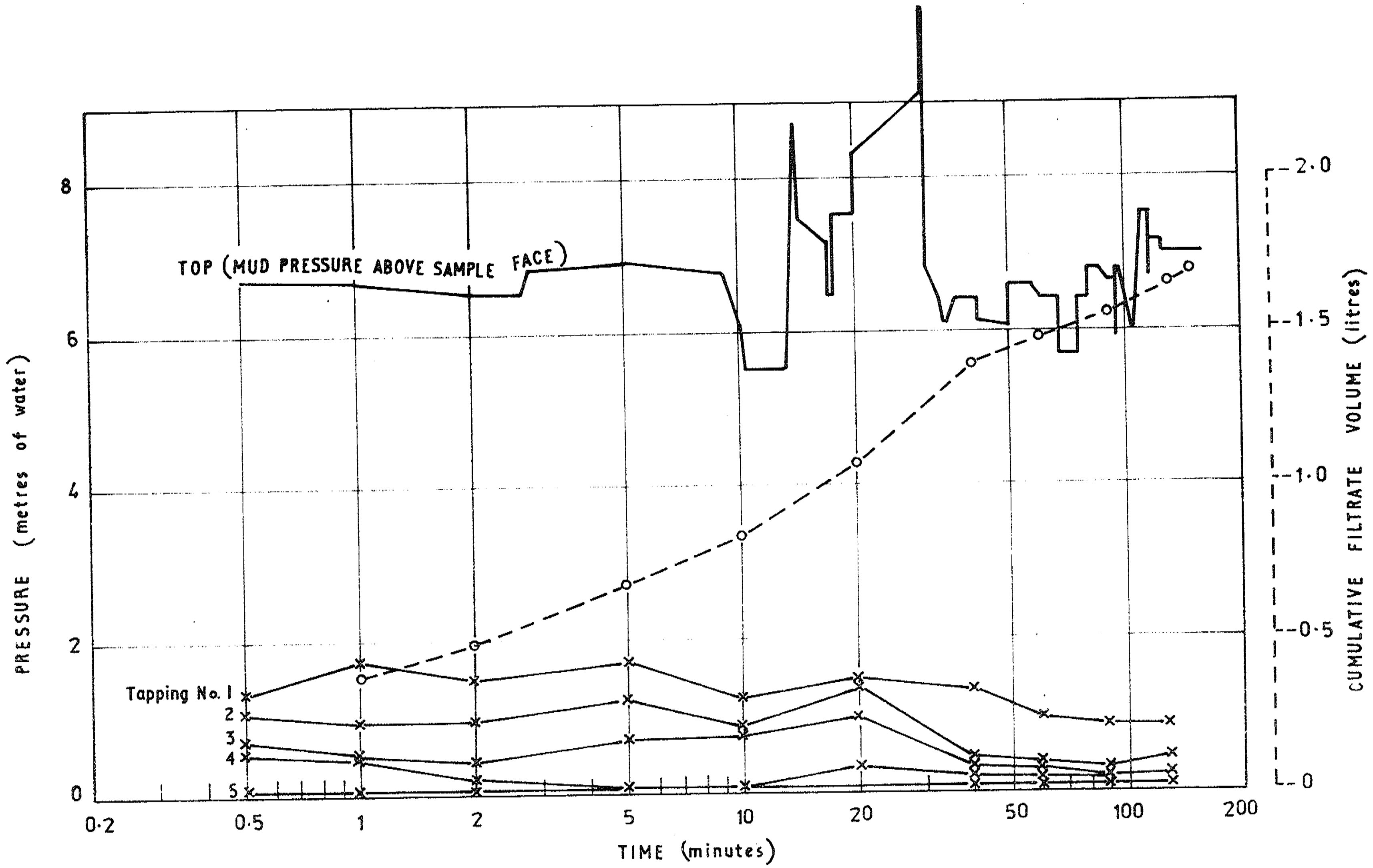


FIGURE 8·7 TEST 008 MATERIAL 1.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

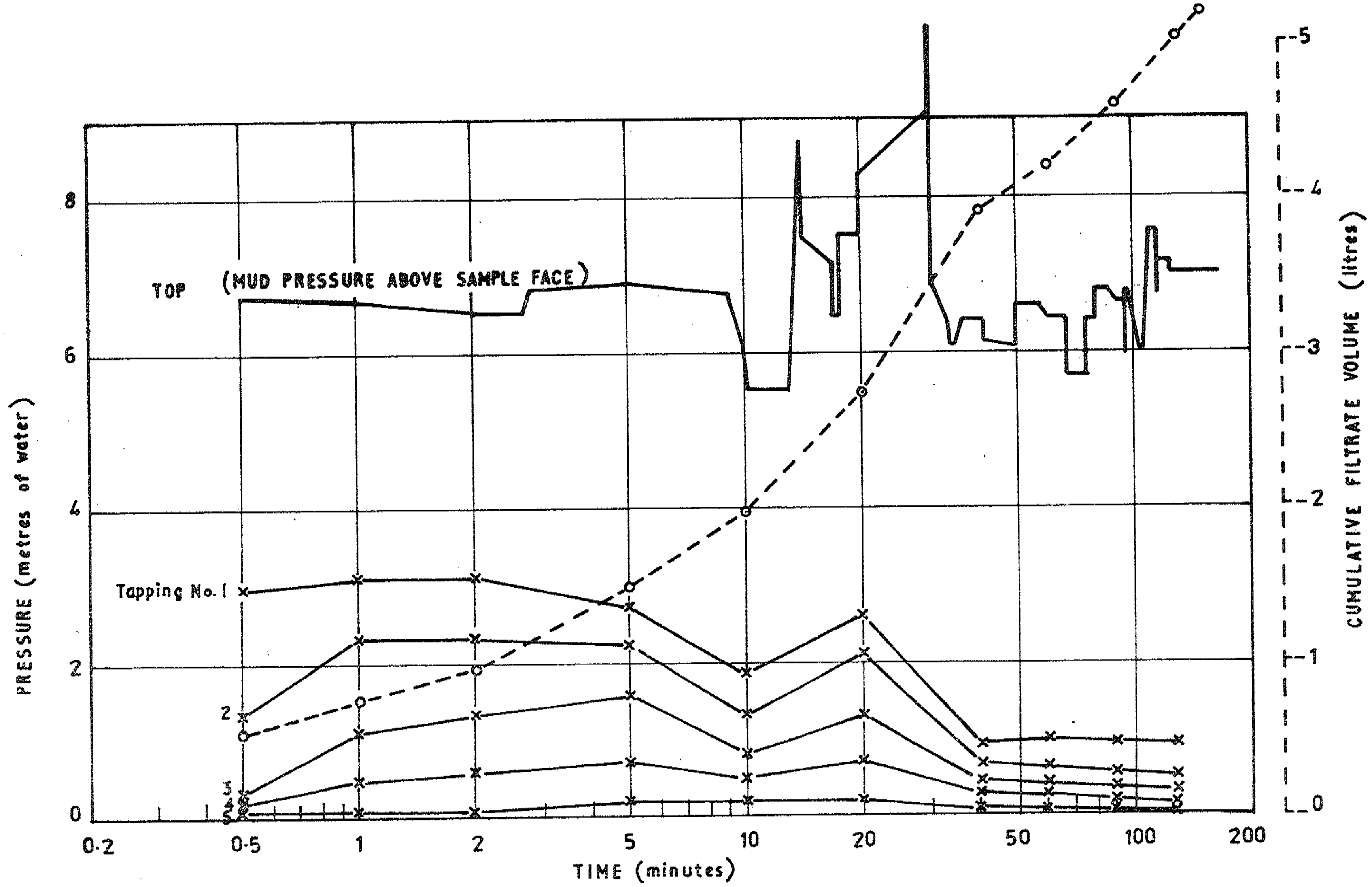


FIGURE 8·8 TEST 008 MATERIAL 2.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

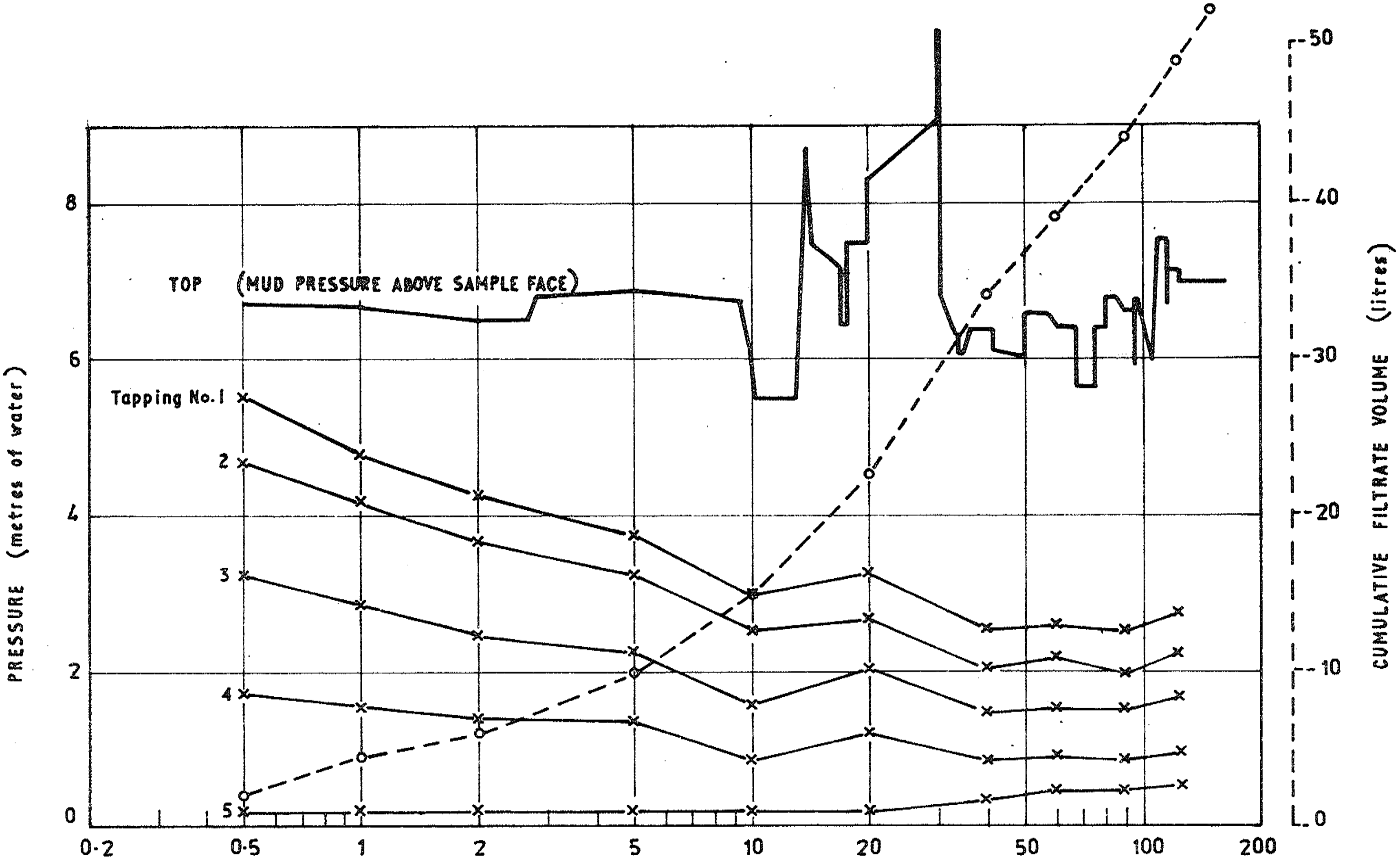


FIGURE 8·9 TEST 008 MATERIAL 3.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

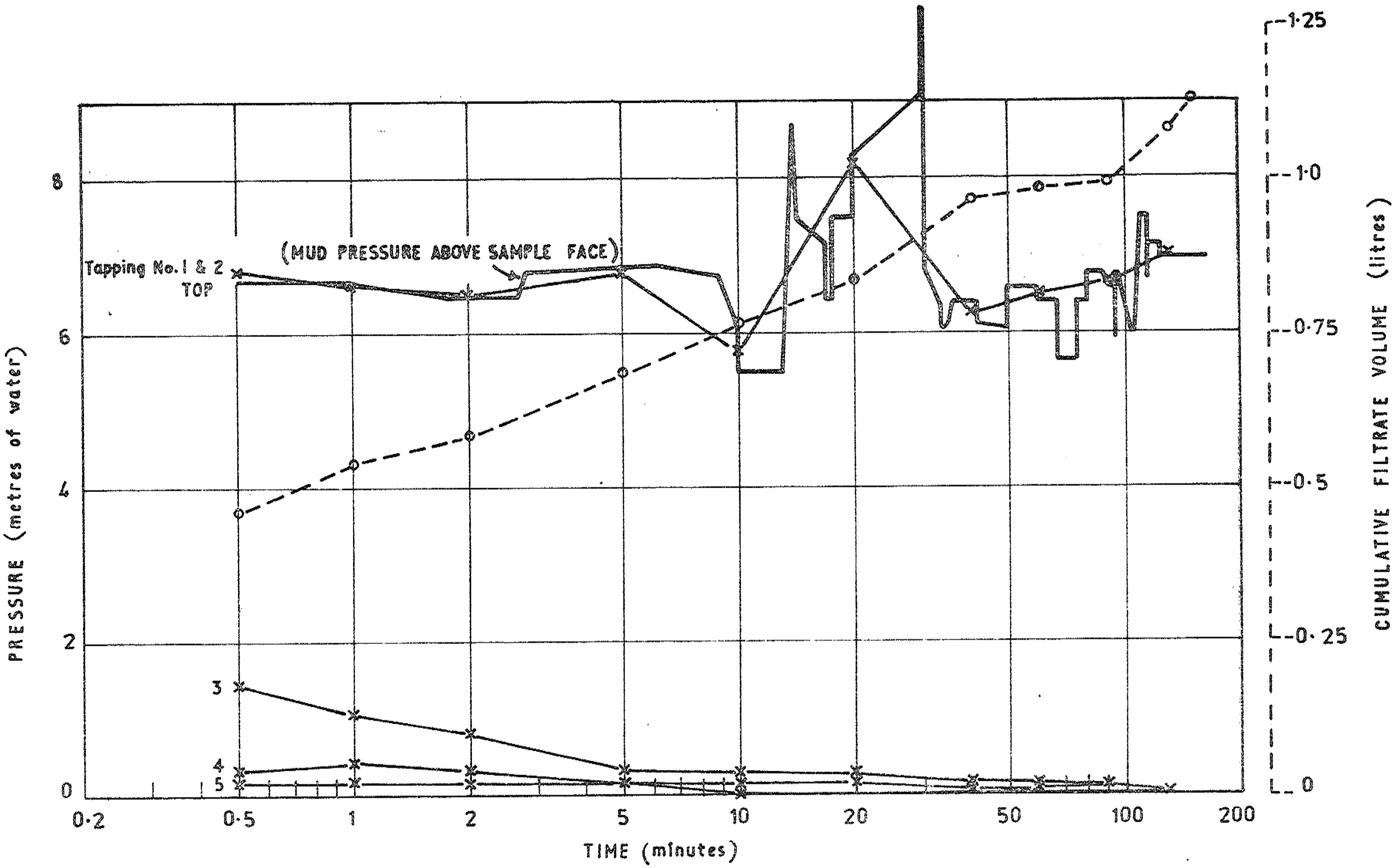


FIGURE 8·10 TEST 008 MATERIAL 6.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD

Table 8.1 Test 008

Permeability testing of material samples.

Values of pressure (metres of water) as recorded at various positions along the sample for a measured flow of water through the sample.

Material	Flow Rate litres/ min.	Velocity mm/ min.	Tapping No. Top	1	2	3	4	5
			Position along sample from datum (mm)					
			0	64	114	216	318	420
Material Tests before Exposure to Drilling Mud								
3	37.04	5760	14.90	13.42	11.91	9.20	6.11	3.34
	27.95	4350	9.78	8.51	7.50	5.67	3.72	1.89
	16.48	2560	4.13	3.59	3.15	2.33	1.45	0.57
2	14.84	2310	16.01	14.56	12.54	9.26	5.23	1.83
	9.79	1520	9.52	8.63	7.37	5.36	2.96	.95
	5.13	798	4.17	3.85	3.34	2.33	1.26	.32
1	4.76	740	15.59	13.74	12.16	8.76	5.11	1.70
	3.21	499	10.09	8.89	7.75	5.48	3.09	.89
	1.67	259	4.66	4.48	3.85	2.71	1.52	.38
6	6.28	976	15.36	15.19	14.81	12.29	6.24	2.59
	4.36	678	9.55	9.52	9.14	7.37	3.53	1.58
	2.00	311	3.59	3.72	3.66	2.84	1.39	0.89
Material Tests after Exposure to Drilling Mud Initial Flushing - Water Only								
3	20.94	326	13.99	12.60	11.15	8.26	4.73	1.70
	16.09	250	9.33	8.32	7.31	5.36	3.09	1.07
	9.55	149	3.75	3.47	2.96	2.15	1.20	.38
2	8.96	139	14.75	11.53	9.64	6.62	3.53	.95
	5.53	85.9	8.64	6.43	5.30	3.59	1.83	.44
	2.68	41.7	3.97	2.90	2.40	1.64	.89	.26
1	2.11	32.8	14.68	8.00	6.87	4.73	2.84	.89
	1.15	17.8	9.63	4.22	3.66	2.52	1.64	.57
	0.37	5.76	3.90	1.45	1.20	.89	.76	.26
6	.91	14.1	14.68	14.56	14.56	3.34	.82	.19
	.39	6.06	8.52	8.95	8.89	1.33	.32	.13

Table 8.1 Test 008 (cont'd.)

Material	Flow Rate litres/ min.	Velocity mm/ min.	Tapping No.					
			Top	1	2	3	4	5
			Position along sample from datum(mm)					
			0	64	114	216	318	420
Material Tests after Exposure to Drilling Mud Final Flushing - P.B.D. Treatment and Further Water Flushing								
3	25.97	404	13.45	12.48	11.15	8.51	5.17	2.15
	20.33	316	8.94	8.26	7.37	5.61	3.34	1.33
	12.50	194	3.75	3.59	3.22	2.40	1.39	.51
2	6.38	99.2	14.29	12.67	11.15	7.82	4.16	1.07
	4.15	64.5	9.63	8.63	7.63	5.36	2.84	.70
	1.77	27.4	3.36	3.15	2.78	2.02	1.33	.32
1	3.61	56.2	14.45	12.35	10.90	7.44	4.04	1.20
	2.20	34.2	8.79	7.50	6.62	4.48	2.46	.70
	.85	13.2	3.55	3.22	2.84	1.96	1.01	.32
6	1.88	29.2	14.29	14.18	13.67	7.50	2.84	.95
	1.34	20.8	9.63	9.64	9.52	4.73	1.77	.57
	.64	9.95	3.75	3.91	3.91	1.77	.63	.19

Table 8.2 Test 008

Sample behaviour during time of exposure to Hydropol drilling fluid.

Pressure (metres of water)

Material	Time (minutes)	Filtrate Volume (litres)	Tapping No.					
			Top	1	2	3	4	5
			Position along sample from datum (mm)					
			0	64	114	216	318	420
1	½			1.33	1.07	0.70	0.57	.07
	1	.38	6.65	1.70	0.95	0.51	0.44	.07
	2	.48	6.50	1.45	0.95	0.44	0.19	.07
	5	.68	6.88	1.70	1.2	0.70	0.07	.07
	10	.83	6.04	1.20	0.82	0.70	0.07	.07
	20	1.06	8.33	1.45	1.32	0.95	0.32	.07
	40	1.38	6.42	1.33	.44	.32	.19	.07
	60	1.47	6.42	.95	.38	.32	.19	.07
	90	1.55	6.57	.82	.26	.19	.19	.07
	133	1.65	6.96	.82	.44	.19	.19	.07
	150	1.68	6.96					
2	½	.545		2.96	1.33	0.32	0.19	0.07
	1	.765	6.65	3.09	2.33	1.07	0.44	0.07
	2	.965	6.50	3.09	2.33	1.33	0.57	0.06
	5	1.495	6.88	2.71	2.21	1.58	0.70	0.19
	10	1.975	6.04	1.83	1.33	0.82	0.44	0.19
	20	2.735	8.33	2.59	2.08	1.33	0.70	0.19
	40	3.895	6.42	.95	.70	.44	.26	.07
	60	4.195	6.42	1.01	.63	.44	.26	.07
	90	4.595	6.57	.95	.57	.38	.19	.07
	133	5.035	6.96	.95	.51	.32	.13	.07
	150	5.195	6.96					
3	½	2.0		5.48	4.65	3.22	1.70	0.19
	1	4.5	6.65	4.73	4.15	2.84	1.58	.19
	2	6	6.50	4.22	3.64	2.46	1.45	.19
	5	10	6.88	3.72	3.22	2.21	1.33	.19
	10	15	6.04	2.96	2.46	1.58	0.82	0.19
	20	22.5	8.33	3.22	2.64	2.02	1.20	0.19
	40	34	6.42	2.52	2.02	1.45	.82	.32
	60	39	6.42	2.59	2.15	1.52	.89	.44
	90	44	6.57	2.52	1.96	1.45	.82	.44
	124	49	6.96	2.71	2.21	1.64	.95	.51
	150	52.1	6.96					

Table 8.2 Test 008 (cont'd.)

Material	Time (minutes)	Filtrate Volume (litres)	Tapping No.					
			Top	1	2	3	4	5
			Position along sample from datum (mm)					
			0	64	114	216	318	420
6	½	.46		6.80	6.80	1.45	0.32	0.19
	1	.53	6.65	6.65	6.65	1.07	0.44	0.19
	2	.58	6.50	6.50	6.50	0.82	0.32	0.19
	5	.68	6.88	6.80	6.80	0.32	0.19	0.19
	10	.77	6.04	5.80	5.80	0.32	0.19	0.07
	20	.83	8.33	8.20	8.20	0.32	0.19	0.07
	40	.97	6.42	6.24	6.24	.19	.13	.07
	60	.98	6.42	6.49	6.49	.13	.13	.07
	90	.99	6.57	6.62	6.62	.13	.13	.07
	133	1.08	6.96	7.00	7.00	.07	.07	.07
	150	1.13	6.96					

V9 Test 009 Results and Observations

The mud was made up as approximately 0.9% (9 lbs/100 gallons) by weight Hydropol (old stock). The mud was circulated for 2 hours prior to starting the test. The mud properties were tested at various times both before and during the exposure of the sample materials to the mud. The results of such tests were as follows:

Time mins.	Temp. °C	Marsh Funnel Viscosity secs.	API Filter Press (½ area)		Plastic Viscosity cps	Yield Point lb/100ft²
			Initial Spurt (V_s+V_x) cc	Corrected Volume (V_c) cc		
-110	19	34	16.5	5.9	5.8	3
-30	19	35				
+30	19	34	7.3	4.9	6.0	0
+85	19	33				
+125	19	34	6.5	5.1	5.5	0

The specific gravity of the mud was 1.00 - (with the accuracy of the mud balance no difference between the mud and water was noticeable). In all API filter press tests the thickness of the filter cake was negligible.

The mud was circulated at a velocity of 120 ft/min. past the face of the sample materials and a pressure differential of approximately 20 psi was maintained for the exposure duration of 2½ hours.

After the 150 minutes of pressurised mud flow the pump was turned off and the test apparatus was isolated. The pressure was relieved and the mud was left to stand (static flow condition) above the samples for 20 hours.

All mud was drained from above the samples which were removed, inspected and then reinstalled without any disturbance to the material faces. Water was gently washed through the test cell for 20 minutes to clean all mud from the apparatus.

The apparatus was filled with water and each material flushed through under applied pressures up to 20 psi until no further improvement in flow could be obtained.

Each sample was retested for permeability.

Romud P.B.D. in the recommended concentration of 0.75 lb/100 gallons was added to the test apparatus. After 15 minutes, fluid was flushed through each material until the pH change indicated that P.B.D. solution was present throughout the sample length. Each sample was left as such for 17 hours before further flushing was carried out to achieve optimum sample rehabilitation.

The samples were then retested for permeability to estimate the extent of permanent damage caused by exposure to the mud system.

The samples were left covered with water for 16 hours before being finally removed and inspected.

Note: This test was similar in all aspects to test 008 other than the applied pressure differential which has been increased from approximately 10 to 20 psi.

Material 1

Porosity = 38%

(original) Linear K_O = 19 mm/min
Table 9.1, Figures 9.1a, 9.5)

See Table 9.2 and Figure 9.6. Within ½ minute of exposure a seal formed somewhere in the top 64 mm of the sample which accounted for a pressure drop from 14 metres at the exposed face to 3.2 metres of water head at tapping 1. The effectiveness of this seal decreased for the next few minutes. After 5 minutes of exposure the effectiveness of the seal continually increased until at the end of the test (150 minutes) the pressure drop between the sample face and tapping 1 was from 13.7 to 1.0 metres of water.

The developed seal was considerably less effective in prohibiting loss of mud filtrate to the material than those seals formed in previous tests using bentonite muds. Although the mud filtrate loss rate decreased in time it was still approximately 9 cc/min. at the end of the test. The mud filtrate would have penetrated the entire sample length after only 4 minutes when the collected filtrate volume was 1.1 litres. The total volume of filtrate collected was 4.92 litres.

The effectiveness of the hydropol mud in prohibiting water loss appears to be very much pressure dependent. In the previous test 008, at a lower pressure differential of 10 psi, a total volume of only 1.68 litres was collected and the final loss rate was less than 2 cc/min.

When the sample was removed, a distinct 1 mm thick sealing layer was evident at the exposed face of the material. The remainder of the sample appeared to be homogeneous.

The sample was replaced and all mud washed from the test cell with water. The apparatus was filled with water and pressure applied to flush the sample. A small but noticeable improvement was achieved with an extensive period of flushing. The sealing layer in the top 1 mm of the sample was still quite effective in limiting flushing velocities, thus preventing further rehabilitation.

The results of permeability testing after water flushing alone are now given:

(exposed) 5-216 mm Linear K_e = 10 mm/min
216-450 mm Linear K_e = 15 mm/min.
(Table 9.1, Figures 9.1b, 9.5

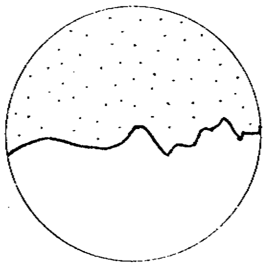
The 1 mm seal in the top of the sample was still quite apparent (Figure 9.1b) although its effectiveness had been reduced by water flushing alone.

Beyond the seal itself there had been permeability reductions of 47% and 21% for the material between 5-216 mm and 216-450 mm respectively.

After P.B.D. treatment and further water flushing the material was again tested for permeability. From Figure 9.1b, the 1mm sealing layer at the surface of the material had been broken by the P.B.D. treatment and the entire sample now had a permeability of 15 mm/min. (Figure 9.5).

The P.B.D. solution had been effective in breaking down the sealing layer where water flushing had only limited success. However, the entire sample had undergone permanent damage with a permeability reduction of 21% being recorded.

When the sample was finally removed and inspected, the 1 mm sealing layer at the surface of the sample (previously noted in an earlier inspection) was seen to be still intact over 50% of the area of the face of the material. No evidence of the seal was present over the other 50% of the sample face. A sketch of the sample face was made.



The remainder of the material appeared to be homogeneous.

Material 2

Porosity = 38.6%

(original) Non-linear $K_o = 1/a$ = 100 mm/min, b/a^2 = .05
(Table 9.1, Figure 9.2a, 9.5)

See Table 9.2 and Figure 9.7. A relatively minor degree of sealing had occurred somewhere in the top 64 mm of the sample within the first $\frac{1}{2}$ minute of exposure. This was indicated by the pressure drop from 14.0 metres at the exposed face to 6.62 metres of water at tapping 1. The effectiveness of this seal improved with time of exposure until after 150 minutes the pressure drop between the sample face and tapping 1 was 12.2 metres of water.

The mud filtrate flow rate was reduced from approximately 1 litre/min at $\frac{1}{2}$ minute to 10 cc/min. at 150 minutes. Whole mud filtrate flowed from the sample after only 1 minute of exposure. Although the mud filtrate loss rate decreased in time, the flow rate at the end of the test was still substantial and a total volume of 8.14 litres was collected.

The seal developed in this test was far less effective in limiting loss of mud filtrate to the material than those seals previously developed in tests using bentonite muds.

The seal developed in this test was noticeably less effective than the one formed in Test 008 using the same mud system but a lower pressure differential of 10 psi. In test 008, a total volume of only 5.2 litres was collected. As noted for material 1, the continued loss of mud filtrate through the hydropol mud seal was pressure dependent.

When the sample was removed, a distinct 1 mm thick sealing layer was evident at the exposed face of the material. The remainder of the sample appeared to be homogeneous.

The sample was replaced and all mud washed from the test cell with water. The apparatus was filled with water and pressure applied to flush the sample. A small but noticeable improvement was achieved after extensive flushing under pressures up to 20 psi. The sealing layer in the top 1mm of the sample was still quite prominent and limited the flushing velocities, thus preventing further rehabilitation of the sample.

The results of permeability testing after water flushing alone are now given:

(exposed) 5-114 mm Non-linear $K_e = 1/a$ = 30 mm/min, b/a^2 = .022
114-216 mm Non-linear $K_e = 1/a$ = 36 mm/min, b/a^2 = .018
216-318mm Non-linear $K_e = 1/a$ = 44 mm/min, b/a^2 = .013
318-450mm Non-linear $K_e = 1/a$ = 56 mm/min, b/a^2 = .027
(Table 9.1, Figures 9.2b, 9.5)

The 1 mm seal in the top of the sample was still quite apparent (Figure 9.2b), although its effectiveness had been reduced by water flushing alone.

Beyond the 1 mm seal there was an overall reduction in material permeability which appeared to be graded with distance from the exposed face. Permeability reductions of 70%, 64%, 56% and 44% were indicated for the 5-114, 114-216, 216-318 and 318-450 mm layers respectively.

A similar grading of less severe damage was obtained in test 008.

After P.B.D. treatment and further flushing, the material was again tested for permeability. From Figure 9.2b, the 1mm sealing layer at the sample surface has been broken by the P.B.D. treatment. The material now appeared to be in two layers each of which was of very low permeability.

(exposed) 0-318 mm Linear K_e = 6.3 mm/min.
318-450mm Linear K_e = 8.2 mm/min.
(Table 9.1, Figures 9.2b, 9.5)

These values indicate an overall permeability reduction of approximately 93% for the entire sample.

The P.B.D. treatment had effectively removed the 1 mm seal at the face of the sample which water flushing alone had previously been unable to do.

However, the sample permeability after P.B.D. treatment was much lower than that of the material after rehabilitation by water flushing alone and prior to any P.B.D. treatment. This apparent reduction in permeability with P.B.D. treatment was also noted in test 008 and no logical explanation can be made by the author.

When the sample was finally removed and inspected, remnants of the 1 mm sealing layer were evident in small scattered patches over the face of the sample. The remainder of the material appeared to be homogeneous.

Material 3

Porosity = 39%

(original) Non-linear $K_o = 1/a = 480$ mm/min, $b/a^2 = .15$
(Table 9.1, Figures 9.3a, 9.5)

See Table 9.2 and Figure 9.8. With time of exposure there was a steady but small decrease in permeability of some portion of the sample between the exposed face and tapping 1. The pressure drop across the 0-64 mm layer of the sample increased from 2.6 metres at $\frac{1}{2}$ minute to 5.6 metres of water head at 150 minutes. There was also a noticeable decrease in the permeability of the 64-114 mm portion of the sample as evidenced by the increased proportion of the head loss occurring between tappings 2 and 3.

Whole mud flowed freely from the sample for most of this test. The decrease in permeability in the upper portions of the sample reduced the mud flow rate from 7 litres/minute at $\frac{1}{2}$ minute to 0.4 litres/min. at 150 minutes.

The inability of this hydropol mud to eliminate mud loss to the material is in sharp contrast to the completely effective seal developed by a $6\frac{1}{2}\%$ Aquagel mud in test 004. In test 004 a seal formed within 10 minutes which prevented any further loss of mud filtrate beyond 41 litres.

A total volume of 120 litres of mud filtrate was collected. In test 008 using the same mud system, but a lower pressure differential of 10 psi, 52 litres were collected.

When the sample was removed, a layer of apparently lower permeability was evident in the top 2 mm of the sample. This layer was not a distinct cohesive cake as had been the case with materials 1 and 2 when examined. The remainder of the sample appeared to be homogeneous.

The sample was replaced and all mud washed from the test cell with water. The apparatus was filled with water and pressure applied to flush the sample. The sample was easily cleaned and flushing continued until no further improvement was noticeable.

The results of permeability testing after water flushing are now given:

(exposed) 64-114 mm Non-linear K_e = 1/a = 120 mm/min, b/a^2=.52
114-318 mm Non-linear K_e = 1/a = 180 mm/min, b/a^2=.44
318-450 mm Non-linear K_e =1/a = 340 mm/min, b/a^2=1.2
(Table 9.1, Figures 9.3b, 9.5)

Examining Figure 9.3b, it would appear that water flushing alone had removed the 2 mm layer at the exposed face of the sample.

There was an overall reduction in material permeability which appeared to be graded with distance from the exposed face.

After P.B.D. treatment and further flushing the material was again tested for permeability.

(exposed) 64-114 mm Non-linear K_e = 1/a = 170 mm/min, b/a^2=.36
114-318 mm Non-linear K_e = 1/a = 305 mm/min, b/a^2=.59
318-450 mm Non-linear K_e = 1/a = 400 mm/min, b/a^2 = .80
(Table 9.1, Figures 9.3b, 9.5)

The P.B.D. treatment had significantly aided in the recovery of the sample.

For materials with $b/a^2 > 0.1$, the reliability of extrapolating non-linear equations ($i = aV + bV^2$) as determined from only 3 points to a value of permeability $K = 1/a$ is very low. In such cases, estimates of damage may be more reliably evaluated by comparing the hydraulic gradients necessary to achieve specified flow velocities. For water flushing alone, the indicated reductions in permeability (specified flow velocity = 1500 mm/min) were 95%, 89% and 84% for the 64-114, 114-318, and 318-450 mm layers respectively (Figure 9.5). After P.B.D. treatment and final flushing, the indicated permeability reductions (specified flow velocity = 2000 mm/min) were 89%, 79% and 74% for the 64-114, 114-318 and 318-450 mm layers respectively.

Quite considerable permanent damage had been done to the samples by exposure to the mud. Water flushing alone was limited in its ability to rehabilitate the mud damaged material. P.B.D. treatment followed by final flushing improved the damaged material permeability by approximately 10%. However, resultant damage was still high with permeability reductions in the range of 75% to 90%.

When the sample was finally removed and inspected, the entire sample appeared to be homogeneous except for noticeable but non-distinct remnants of the 2 mm layer previously noted at the face of the sample.

Material 6

Porosity = 30.8%

(original) 0-64 mm More permeable than 64-114 mm
64-114 mm Linear K_o = 64 mm/min.
114-216 mm Non-linear K_o=30 mm/min, b/a^2 = .018
216-318 mm Non-linear K_o = 19 mm/min, b/a^2 = .012
318-450 mm Non-linear K_o = 44 mm/min, b/a^2 = .050
(Table 9.1, Figures 9.4a, 9.5)

As can be seen the sample had various layers of differing permeability throughout its length.

See Table 9.2 and Figure 9.9. Evidence of the development of a sealing layer between tappings 2 and 3 was seen within $\frac{1}{2}$ minute of exposure when the pressure head drop across this distance was 6.7 metres of water. The effectiveness of the seal improved with time until after 20 minutes it appeared stable and for the remainder of the test accounted for a head loss of 11.3 metres of water between 114 and 216 mm.

The fact that the seal developed between 114-216 mm and not

64-114 was quite significant. The critical permeability of the material which will allow formation of a sealing layer had thus been neatly defined as being between 30 and 60 mm/min.

The developed seal did not fully stem the flow of mud filtrate from the sample. The rate of loss of mud filtrate did, however, decline to such an extent that beyond 40 minutes it was never above 4 cc/minute. (In test 008, using the same mud system, but a lower pressure differential of 10 psi the filtrate loss was reduced to 2 cc/minute for times greater than 30 minutes by a seal which developed in a material layer of permeability 40 mm/min.)

The mud filtrate would have penetrated the entire sample length after only $5\frac{1}{2}$ minutes when the collected filtrate volume was 0.89 litres.

When the sample was removed and inspected, a layer of apparently lower permeability was evident in the top 2 mm of the sample. This layer could not be classed as a seal since it was not distinctly cohesive and did not cover the entire face of the sample. Visual banding was evident throughout the sample which coincided with the banding present when the sample was originally prepared.

The sample was replaced and all mud washed from the test cell with water. The apparatus was filled with water and pressure applied. Attempts to flush the sample even under applied pressures of 25 psi met with only minor success due to the continued effectiveness of the sealing layer between tappings 2 and 3.

The results of permeability testing after water flushing alone are now given:

(exposed) 0-64 mm. Comparable to 64 - 114 mm.
64-114 mm Linear K_e = 19 mm/min.
114-216 mm Linear K_e = 0.2 mm/min.
216-318 mm Linear K_e = 1.0 mm/min.
318-450 mm Linear K_e = 11 mm/min.
(Table 9.1, Figures 9.4b, 9.5)

As can be seen the water flushing alone had not been very effective in rehabilitating the damaged sample. The indicated reductions in permeability of the 64-114, 114-216, 216-318 and 318-450 mm layers are 70%, 99%, 95% and 75% respectively.

After P.B.D. treatment, water flushing of the sample was continued at an improved rate and then the sample retested for permeability.

(exposed)	0-64 mm	Comparable to 64-114 mm
	64-114mm	Linear K_e = 42 mm/min.
	114-216mm	Linear K_e = 0.7 mm/min.
	216-318mm	Non-linear $K_e = 1/a$ = 2.3 mm/min, b/a^2 = .020
	318-450mm	Non-linear $K_e = 1/a$ = 7.5 mm/min, b/a^2 = .063

(Table 9.1, Figures 9.4b, 9.5)

The P.B.D. treatment was an improvement over water flushing alone. However, there had still been considerable permanent damage done to the sample resulting in permeability reductions of 34%, 98%, 88% and 80% for the 64-114, 114-216, 216-318 and 318-450 mm layers respectively.

The P.B.D. treatment had only significantly improved the 64-114 mm and 216-318 mm layers of the damaged sample. Negligible improvements within the layer in which the seal developed were possible.

If higher flushing velocities were possible, the sample may have cleaned up considerably more than it did. The sealing layer between 114 and 216 mm was far enough from the sample face to be extremely difficult to erode. Perhaps continued extensive P.B.D. treatment would have reduced the seal's effectiveness.

The sample was finally removed and inspected. Remnants of the 2mm layer of low permeability previously noted at the face of the sample were evident. Banding which existed when the sample was prepared was still evident. As noted in test 008, 20 mm thick bands of finer material appeared regularly spaced throughout the sample. If such a band were the major cause of the head loss between two tappings then permeabilities within such thin layers could be 1/4 the values indicated by assuming the head loss evenly distributed over the material between the two tappings.

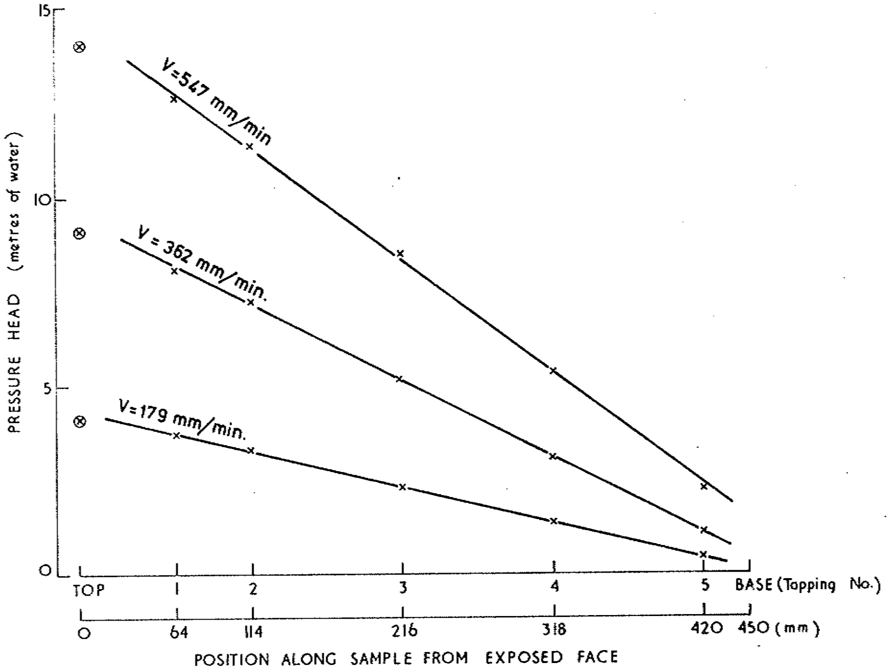


FIGURE 9·1(a) TEST 009 MATERIAL No.1.

Pressure Distributions Before Exposure to Drilling Mud.

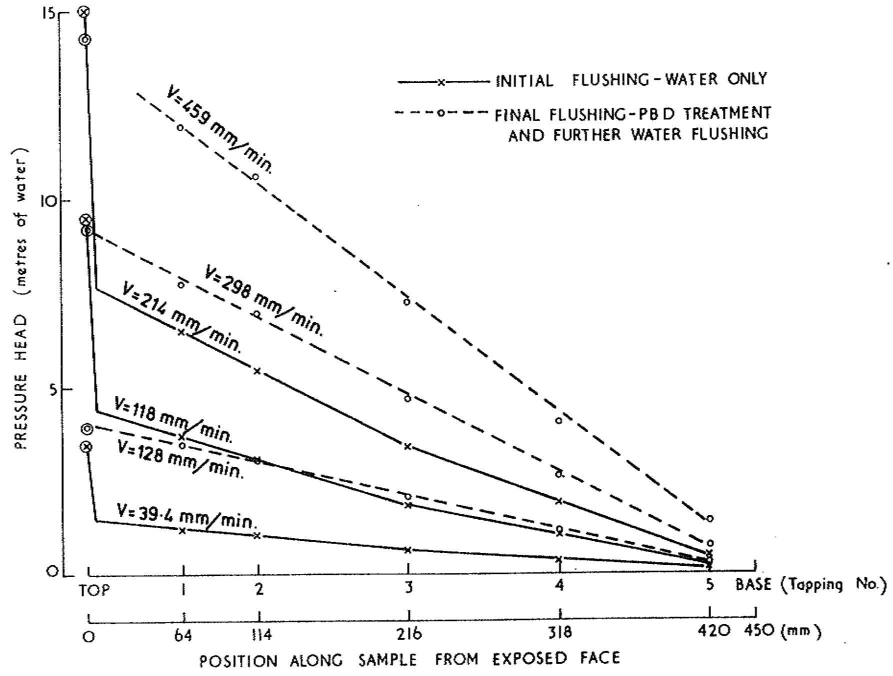


FIGURE 9·1(b) TEST 009 MATERIAL No.1.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

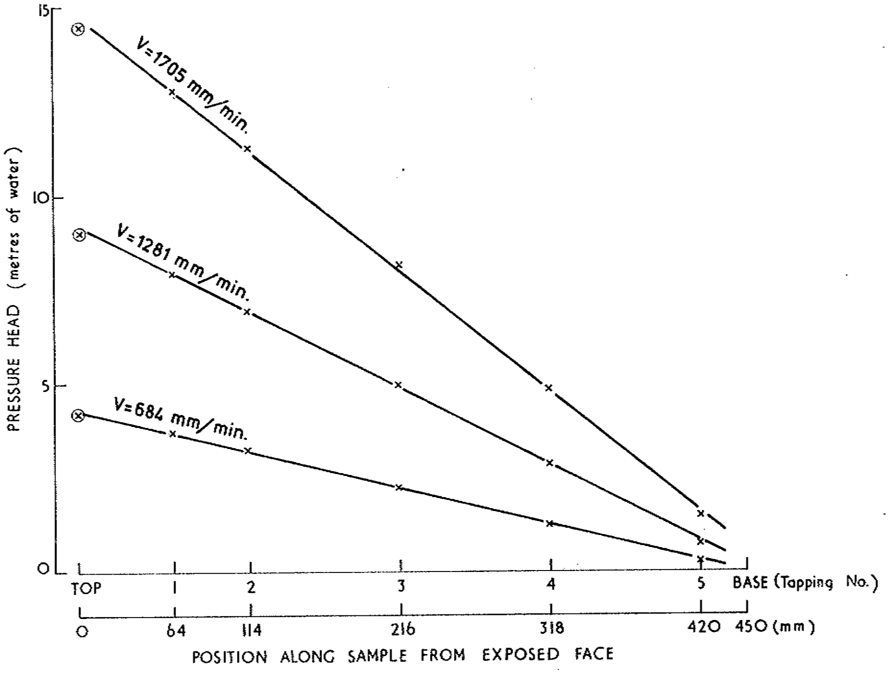


FIGURE 9·2 (a) TEST 009 MATERIAL No. 2.

Pressure Distributions Before Exposure to Drilling Mud.

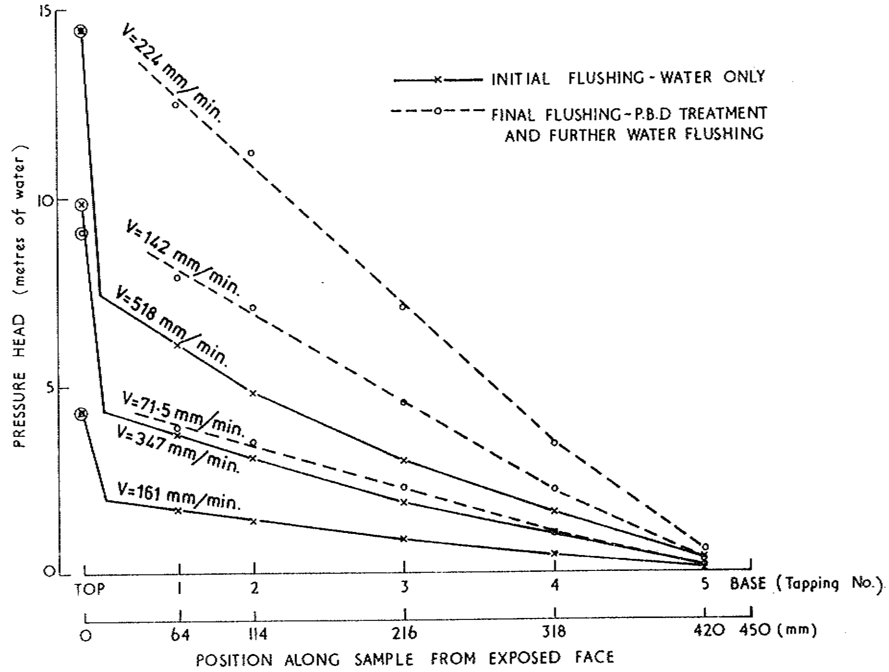


FIGURE 9·2(b) TEST 009 MATERIAL No. 2.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

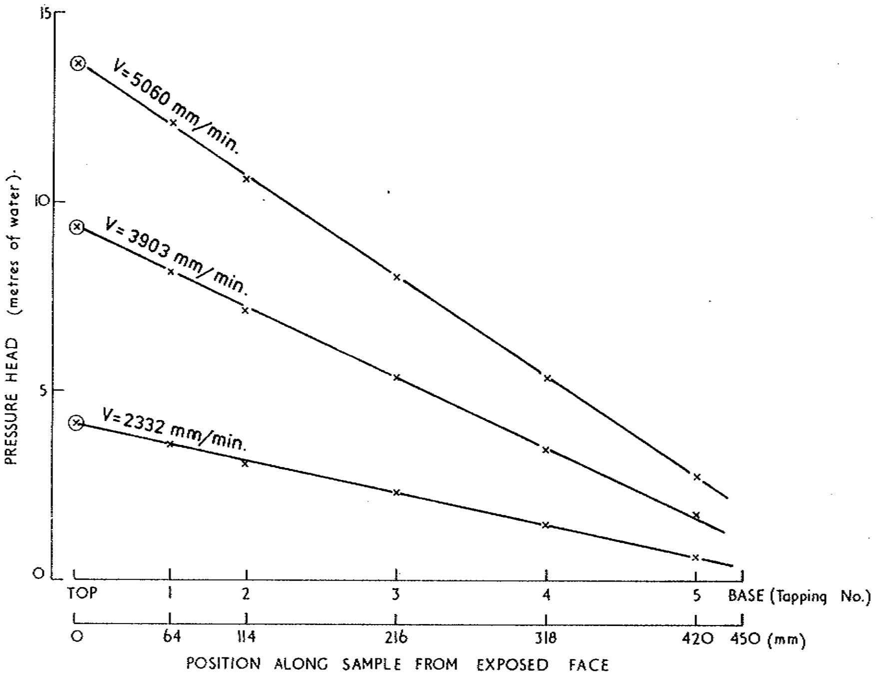


FIGURE 9·3 (a) TEST 009 MATERIAL No. 3.

Pressure Distributions Before Exposure to Drilling Mud.

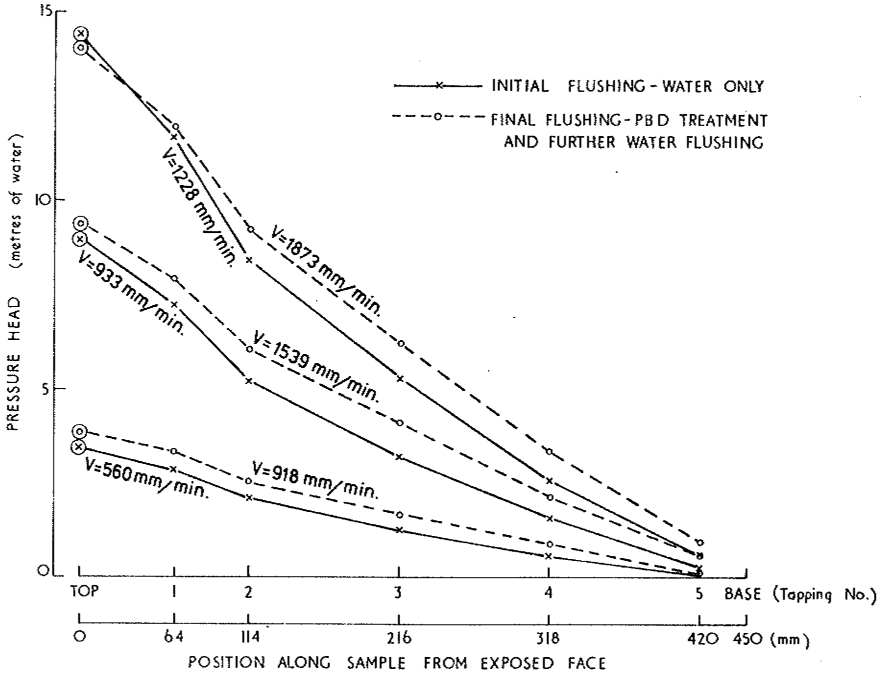


FIGURE 9·3 (b) TEST 009 MATERIAL No. 3.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

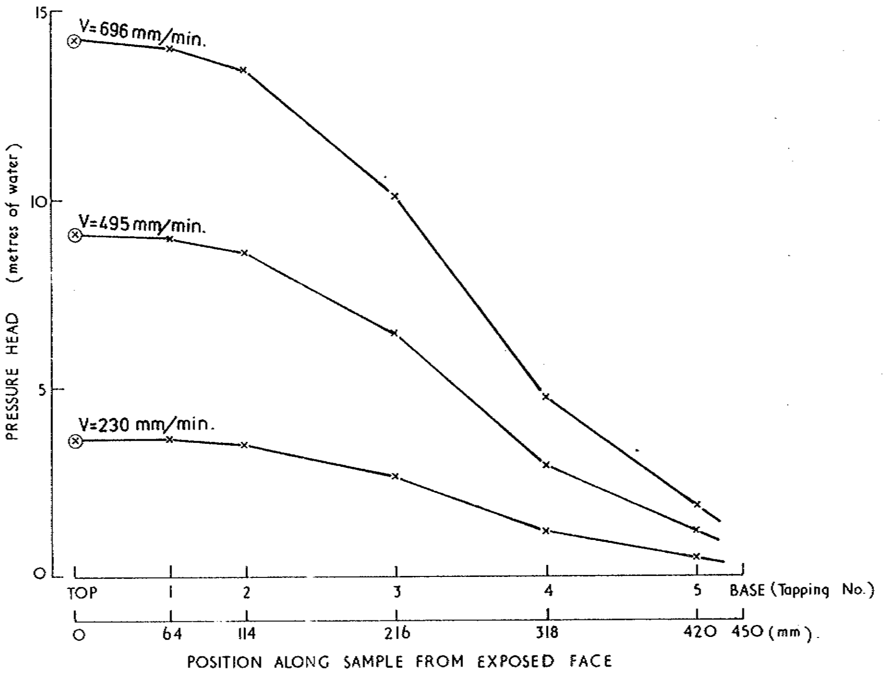


FIGURE 9·4 (a) TEST 009 MATERIAL No.6.

Pressure Distributions Before Exposure to Drilling Mud.

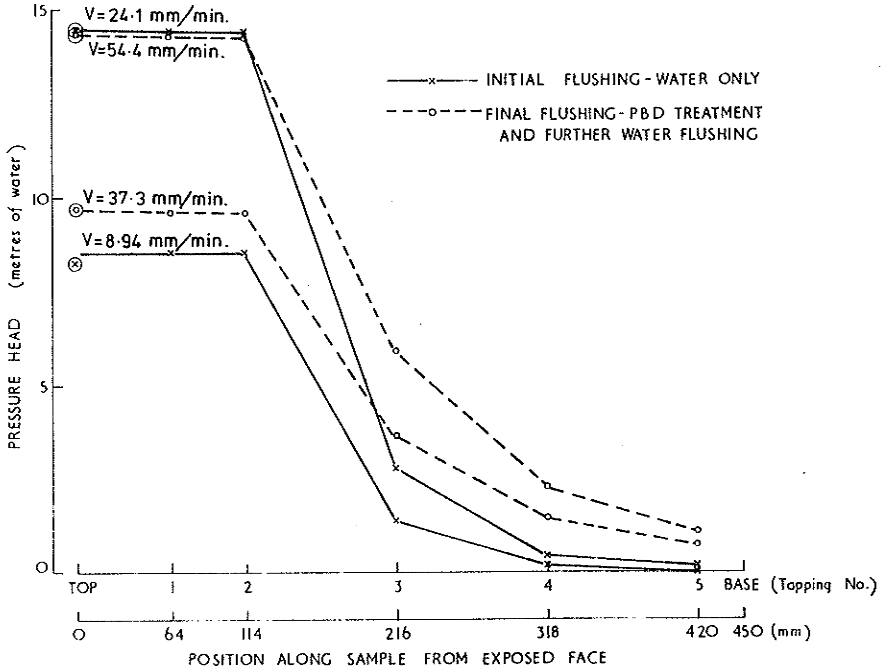
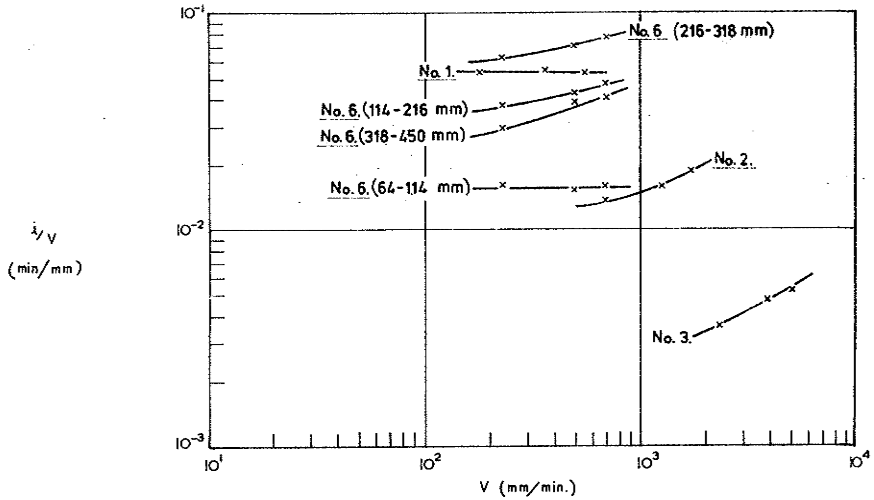
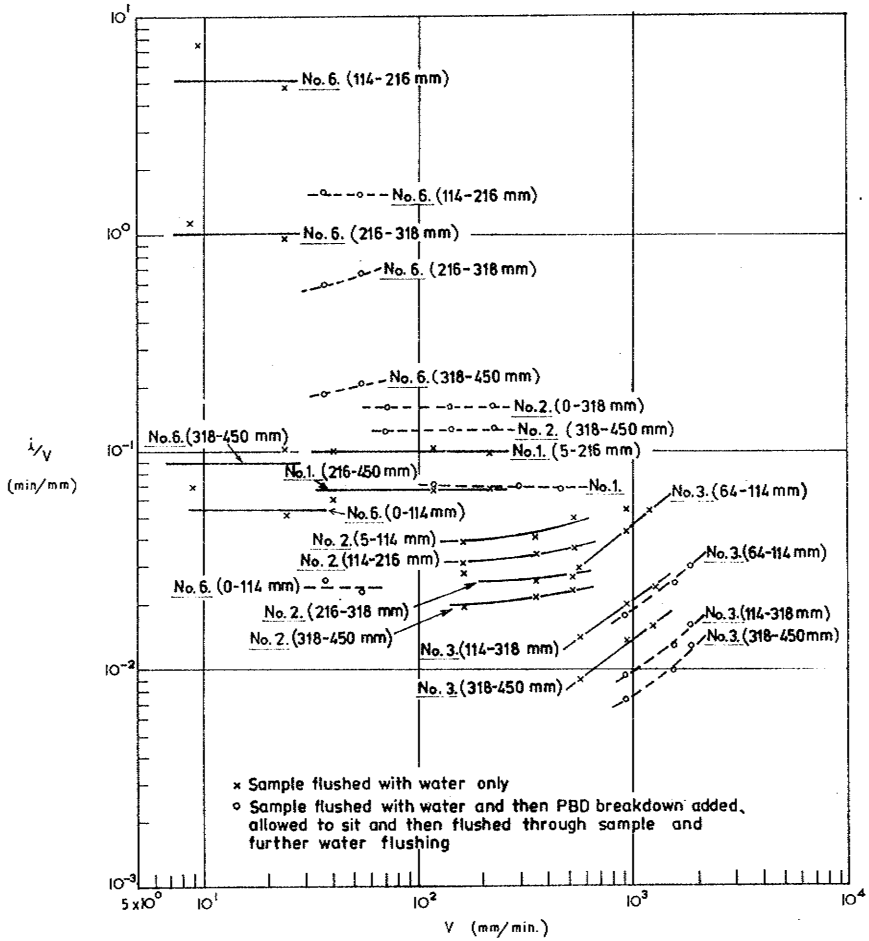


FIGURE 9·4 (b) TEST 009 MATERIAL No.6.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.



(a) Before Exposure to Drilling Mud



(b) After Exposure to Drilling Mud

FIGURE 9·5 **TEST 009**

HYDRAULIC FLOW PROPERTIES OF TEST MATERIALS (i/V versus V)

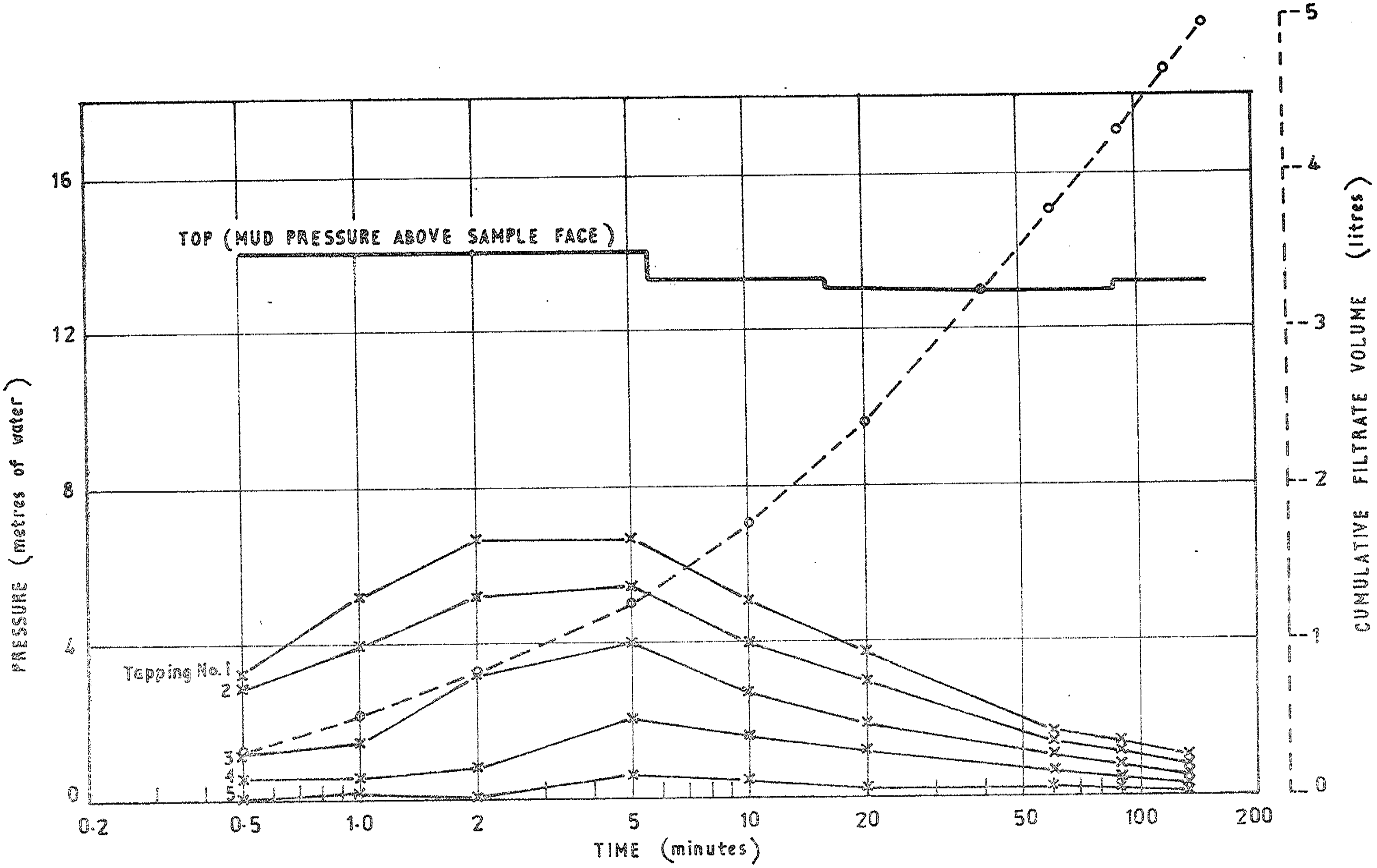


FIGURE 9·6 TEST 009 MATERIAL 1.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

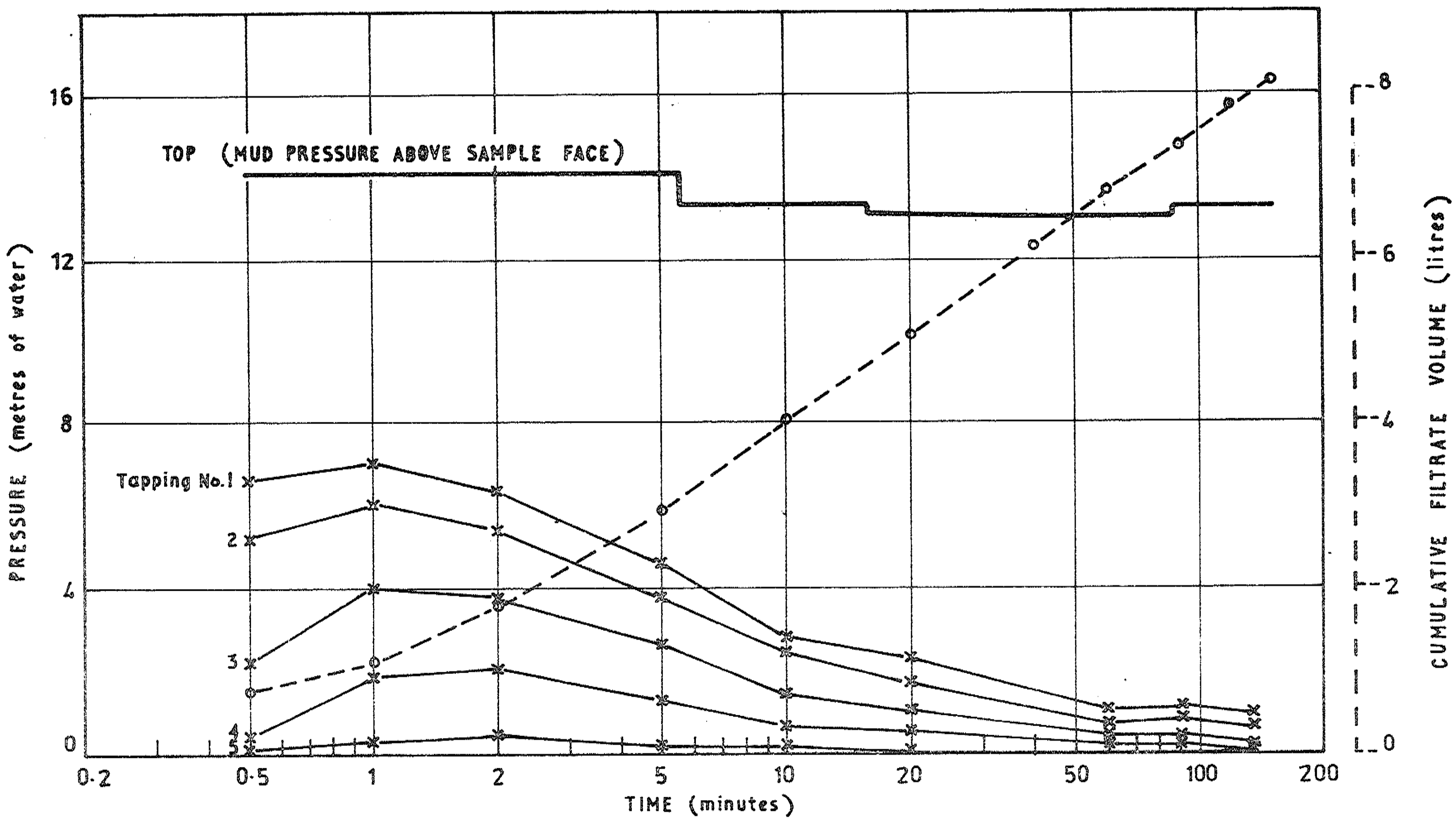


FIGURE 9·7 TEST 009 MATERIAL 2.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

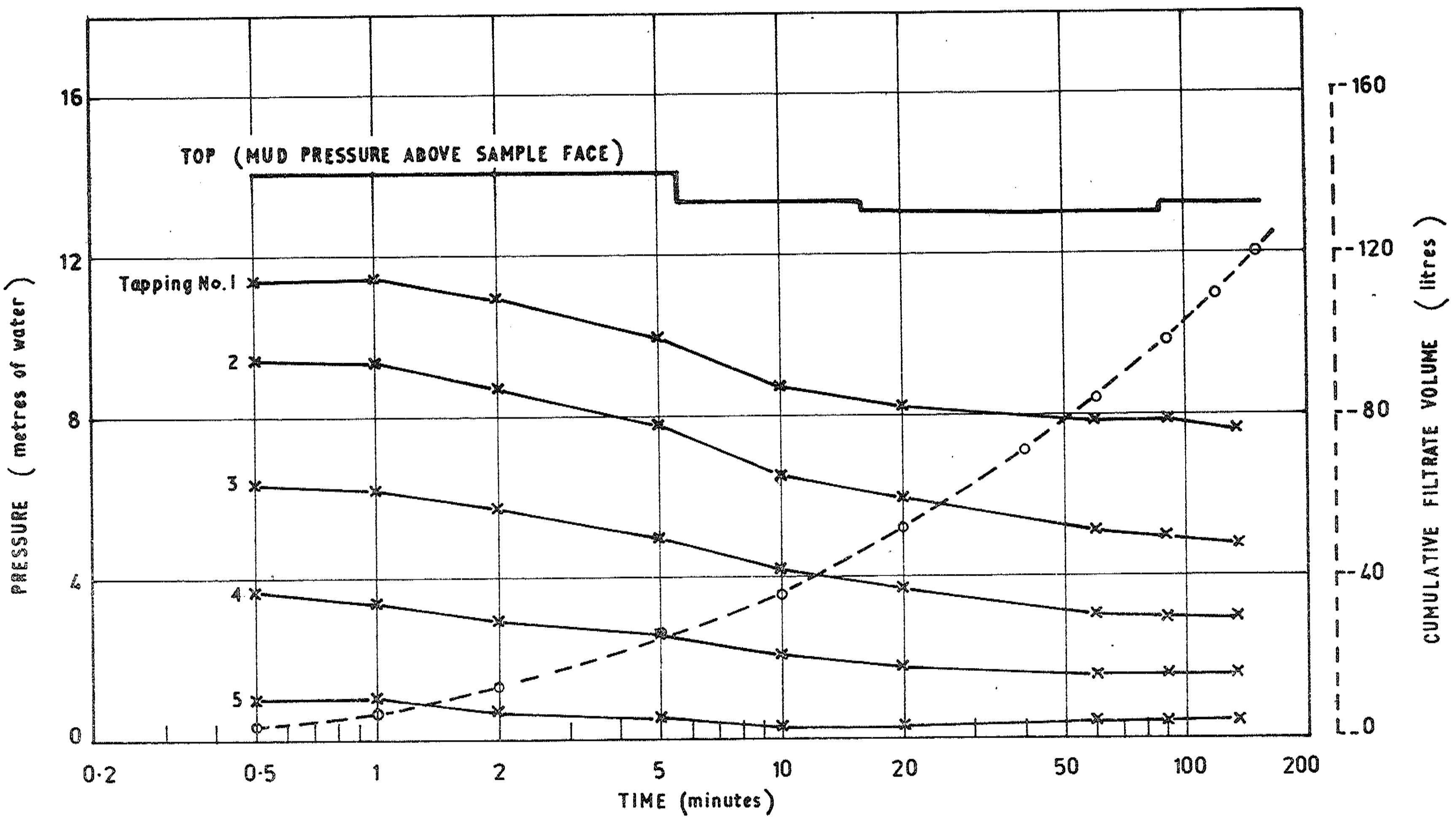


FIGURE 9·8 TEST 009 MATERIAL 3.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

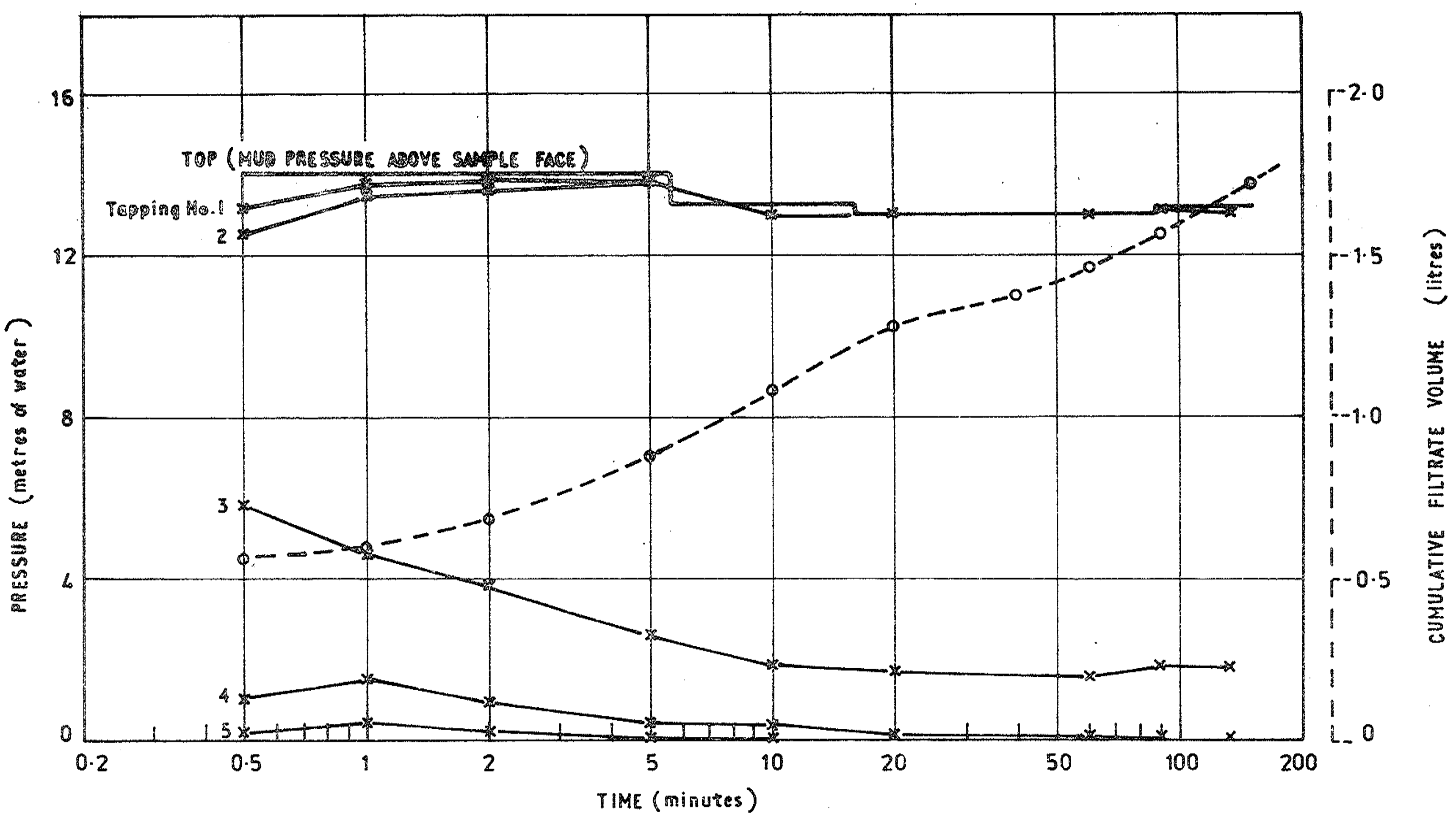


FIGURE 9·9 TEST 009 MATERIAL 6.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

Table 9.1 Test 009

Permeability testing of material samples.

Values of pressure (metres of water) as recorded at various positions along the sample for a measured flow of water through the sample.

Material	Flow Rate litres/min	Velocity mm/min.	Tapping No.					
			Top	1	2	3	4	5
			Position along sample from datum (mm)					
			0	64	114	216	318	420
Material Tests before Exposure to Drilling Mud								
3	32.55	5060	13.68	12.16	10.65	8.07	5.36	2.78
	25.11	3903	9.33	8.13	7.12	5.36	3.47	1.77
	15.00	2332	4.13	3.59	3.09	2.33	1.45	.63
2	10.97	1705	14.45	12.79	11.28	8.19	4.85	1.45
	8.24	1281	9.02	7.94	6.93	4.98	2.84	.76
	4.40	684	4.20	3.72	3.22	2.21	1.26	.32
1	3.52	547	14.06	12.60	11.41	8.51	5.30	2.21
	2.33	362	9.10	8.07	7.25	5.17	3.09	1.07
	1.15	179	4.13	3.72	3.34	2.33	1.39	.44
6	4.48	696	4.29	14.05	13.49	10.15	4.73	1.89
	3.19	495	9.1	9.01	8.63	6.49	2.96	1.20
	1.48	230	3.67	3.72	3.53	2.65	1.20	.51
Material Tests after Exposure to Drilling Mud Initial Flushing - Water only								
3	7.90	1228	14.37	11.66	8.38	5.23	2.52	.57
	6.00	933	8.94	7.19	5.17	3.15	1.52	.26
	3.60	560	3.44	2.88	2.08	1.26	.57	.07
2	3.33	518	14.37	6.05	4.79	2.96	1.58	.38
	2.23	347	9.78	3.72	3.03	1.89	1.01	.26
	1.03	161	4.28	1.70	1.39	.89	.44	.13
1	1.37	214	14.98	6.43	5.36	3.34	1.83	.44
	.76	118	9.40	3.66	3.03	1.83	1.01	.26
	.25	39.4	3.44	1.20	1.01	.60	.32	.13
6	.16	24.1	14.37	14.37	14.30	2.71	.38	.13
	.06	8.94	8.18	8.42	8.38	1.35	.13	.07

Table 9.1 Test 009 (cont'd.)

Material	Flow Rate litres/ min.	Velocity mm/ min.	Tapping No.					
			Top	1	2	3	4	5
			Position along sample from datum(mm)					
			0	64	114	216	318	420
Material Tests after Exposure to Drilling Mud Final Flushing - P. B. D. Treatment and Further Water Flushing								
3	12.05	1873	13.99	11.91	9.14	6.11	3.28	.89
	9.90	1539	9.33	7.88	5.99	4.04	2.08	.57
	5.91	918	3.82	3.32	2.52	1.64	.82	.15
2	1.44	224	14.37	12.41	11.09	7.12	3.41	.57
	.91	142	9.02	7.82	7.00	4.48	2.15	.38
	.46	71.5	4.36	3.85	3.47	2.27	1.07	.19
1	2.95	459	14.22	11.78	10.52	7.19	3.97	1.39
	1.92	298	9.17	7.69	6.87	4.60	2.59	.70
	.83	128	3.86	3.43	3.03	2.02	1.14	.32
6	.35	54.4	14.29	14.178	14.115	5.80	2.21	1.07
	.24	37.3	9.63	9.541	9.491	3.59	1.39	.70

Table 9.2 Test 009

Sample behaviour during time of exposure to drilling mud

Pressure (metres of water)

Material	Time (minutes)	Filtrate Volume (litres)	Tapping No.					
			Top	1	2	3	4	5
			Position along sample from datum (mm)					
			0	64	114	216	318	420
1	½	.305	14.00	3.22	2.84	1.20	0.57	0.07
	1	.530	14.00	5.23	3.97	1.45	0.32	0.19
	2	.805	14.00	6.74	5.23	3.22	0.82	0.07
	5	1.26	14.00	6.74	5.48	3.97	2.08	0.57
	10	1.75	13.22	4.98	3.97	2.71	1.58	0.44
	20	2.40	13.00	3.72	2.96	1.96	1.2	0.19
	40	3.22	13.00					
	60	3.74	12.92	1.64	1.45	.95	.57	.19
	90	4.26	13.22	1.39	1.20	.76	.44	.13
	120	4.66	13.22					
	135		13.22	1.01	.82	.51	.32	.13
	150	4.92	13.22					
2	½	.75	14.00	6.62	5.23	2.21	0.44	0.07
	1	1.10	14.00	7.12	6.11	4.10	1.96	0.32
	2	1.80	14.00	6.37	5.48	3.72	2.08	0.44
	5	2.95	14.00	4.60	3.85	2.71	1.33	0.19
	10	4.05	13.22	2.84	2.46	1.45	0.70	0.19
	20	5.08	13.00	2.33	1.70	1.07	0.57	0.13
	40	6.16	13.00					
	60	6.81	12.92	1.07	.76	.44	.26	.07
	90	7.38	13.22	1.20	.89	.44	.19	.07
	120	7.82	13.22					
	135		13.22	1.01	.63	.26	.13	.07
	150	8.14	13.22					
3	½	3	14.00	11.41	9.52	6.37	3.72	1.07
	1	7	14.00	11.53	2.39	6.24	3.47	1.07
	2	13	14.00	10.90	8.76	5.74	2.96	0.70
	5	25	14.00	10.02	7.75	4.98	2.59	0.57
	10	36	13.22	8.76	6.49	4.22	2.08	0.32
	20	52	13.00	8.26	5.99	3.72	1.83	0.32
	40	71	13.00					
	60	84	12.92	7.94	5.17	3.09	1.58	.44
	90	98	13.22	7.88	5.04	3.03	1.58	.44
	120	110	13.22					
	135		13.22	7.63	4.79	3.03	1.58	.44
	150	120	13.22					

Table 9.2 Test 009 (cont'd.)

Material	Time (minutes)	Filtrate Volume (litres)	Tapping No.					
			Top	1	2	3	4	5
			Position along sample from datum (mm)					
			0	64	114	216	318	420
6	½	.56	14.00	13.17	12.54	5.86	1.07	0.19
	1	.60	14.00	13.80	13.55	4.60	1.58	0.44
	2	.68	14.00	13.80	13.67	3.84	0.95	0.32
	5	.88	14.00	13.93	13.93	2.59	0.44	0.07
	10	1.08	13.22	13.04	13.04	1.96	0.44	0.07
	20	1.28	13.00	13.04	13.04	1.70	0.19	0.07
	40	1.375	13.00					
	60	1.46	12.92	12.92	12.92	1.58	.13	.07
	90	1.56	13.22	13.23	13.17	1.89	.07	.07
	120	1.64	13.22	13.17	13.17	1.83	.07	.07
	135		13.22					
	150	1.715	13.22					

V10 Test 010 Results and Observations

The mud was made up as approximately 0.6% (6 lbs/100 gallons) by weight of Hydropol (new product). As previously noted the new product Hydropol is far more viscous than the old product. The mud was circulated for $1\frac{1}{2}$ hours prior to starting the test. Only limited testing of the mud was carried out during the 40 minute duration of the test. Mud properties as measured were maintained as follows for the duration of the test.

Temperature = $20\frac{1}{2}^{\circ}C$

Specific Gravity = 1.00

Marsh Funnel Viscosity = 45 seconds

Plastic Viscosity = 10.5 cps

Yield = 15 $lb/100\ ft^2$.

The mud was circulated at a velocity of 130 ft/min. past the face of the sample materials and a pressure differential of approximately 20 psi was maintained for the exposure duration of 40 minutes.

It was intended to expose the samples to mud flow for $2\frac{1}{2}$ hours. However, a broken seal in the pump caused the test to be stopped after only 40 minutes. The pressure was relieved and the mud was left to stand (static flow condition) above the samples for 70 hours.

All mud was drained from above the samples which were removed, inspected and then replaced without any undue disturbance. Water was gently washed through the test cell for 20 minutes to dean all mud from the apparatus.

The apparatus was filled with water and each material flushed through under applied pressures up to 20 psi until no further improvement in flow could be obtained.

Each sample was retested for permeability.

Romud P.B.D. in the recommended concentration of 0.75 lb/100 gallons was added to the test apparatus and left to stand above the samples for 17 hours.

Fluid was flushed through each material until the pH change indicated that P.B.D. solution was present throughout the sample length. Each sample was left as such for a further 4 hours before further flushing was carried out to achieve optimum sample rehabilitation.

The samples were then retested for permeability to estimate the extent of permanent damage caused by exposure to the mud flow.

The samples were left covered with water for 12 hours before being finally removed and inspected.

Material 1

Porosity = 38.2%

(original) Linear K_o = 18 mm/min
(Table 10.1, Figures 10.1a, 10.5)

See Table 10.2 and Figure 10.6. Within $\frac{1}{2}$ minute of exposure a seal formed somewhere in the top 64 mm of the sample which accounted for a pressure drop from 13.9 metres at the exposed face to 1.7 metres of water head at tapping 1. The effectiveness of this seal steadily decreased in time for 20 minutes. After 20 minutes of exposure the material behaviour appeared to have stabilised. The pressure drop in the top 64 mm of the sample was only 4.6 metres of water for the remainder of the test. Under similar flow conditions, the old stock Hydropol mud used in test 009 formed a seal in the top 1 mm of the sample which accounted for a pressure drop of 10.6 metres of water.

Although the mud filtrate loss decreased in time, it was still approximately 20 cc/min at the end of the test at which time a total volume of 1.6 litres had been collected. The equivalent loss rate of mud filtrate and collected volume recorded at 40 minutes in test 009 were 28 cc/min and 3.2 litres respectively. The loss of filtrate for the new product Hydropol is far lower than the old stock product used in test 009 due to much higher viscosity.

The mud filtrate would have penetrated the entire sample length after 15 minutes when the collected filtrate volume was 1.2 litres.

When the sample was removed, an approximately 5 mm thick layer of lower pemeability material was evident in the top 5 mm of the sample. This layer was not a distict cohesive impermeable cake and did not cover the entire exposed surface of the sample. The remainder of the sample appeared to be homogeneous.

The sample was reinstalled. The apparatus was cleaned of mud and filled with water. The sample appeared to be quite easily flushed when a pressure of 10 psi was applied. Flushing under a pressure of 20 psi was continued until no further improvement was noted.

The results of permeability testing after water flushing alone for the sample beyond the 5 mm top layer were:

(exposed) Linear K_e = 16 mm/min.
(Table 10.1, Figures 10.1b, 10.5)

As shown in Figure 10.1b, the 5 mm thick layer at the top of the sample was still present. The remainder of the sample appeared to be homogeneous and had suffered a small permeability reduction of 11%.

After P.B.D. treatment and further water flushing the material was again tested for permeability. From Figure 10.1b, the low permeability 5mm thick layer at the top of the sample had been rehabilitated, and the entire sample had a permeability of 15 mm/min.

The P.B.D. treatment had been effective in breaking the low permeability layer at the surface of the sample where water flushing had only limited success. However, the entire sample had undergone a permanent reduction in permeability of approximately 15%.

When the sample was finally removed and inspected, only minor remaining evidence of the previously noted 5 mm thick surface layer could be found. The entire sample appeared to be homogeneous.

Material 2

Porosity = 40%

(original) Non-linear $K_o = 1/a$ = 77 mm/min, b/a^2 = .020
(Table 10.1, Figures 10.2a, 10.5).

See Table 10.2 and Figure 10.7. Only minor evidence of a reduction in permeability between the exposed face and tapping 1 was present with the limited duration of the test. The final pressure drop across the top 64 mm of the sample was only 5.5 metres of water head.

Under similar flow conditions, the old stock Hydropol mud used in test 009 formed a seal within the top 1 mm of the sample which accounted for a pressure drop of 12 metres of water.

Although the mud filtrate loss decreased in time, it was still approximately 70 cc/min. at the end of the test at which time a total volume of 4.7 litres had been collected. The equivalent total volume collected at 40 minutes in test 009 using the less viscous old stock Hydropol was 6.2 litres.

Mud filtrate would have penetrated the entire sample length after only 4½ minutes when the collected filtrate volume was 1.16 litres.

When the sample was removed, a thin 1 mm layer of low permeability was evident at the exposed surface of the sample. This layer was not distinctly cohesive nor highly impermeable. The remainder of the sample appeared to be homogeneous.

The sample was reinstalled. The apparatus was cleaned of mud and filled with water. The sample appeared to be quite easily flushed when a pressure of 10 psi was applied. Flushing under a pressure of 20 psi was continued until no further improvement was noted.

The results of permeability testing after water flushing alone are now given for the material beyond the 1 mm layer at the exposed surface.

(exposed) Non-linear $K_e = 1/a = 52$ mm/min, $b/a^2 = .013$
(Table 10.1, Figures 10.2b, 10.5)

As shown in Figure 10.2b, the 1 mm layer at the sample surface was still present. The remainder of the sample appeared to be homogeneous and had suffered a permeability reduction of 32%.

After P.B.D. treatment and further water flushing the material was again tested for permeability. From Figure 10.2b, the P.B.D. treatment had removed the seal caused by the 1 mm layer and the entire sample appeared to be homogeneous with the following flow behaviour:

(exposed) Non-linear $K_e = 1/a = 28$ mm/min, $b/a^2 = .008$
(Table 10.1, Figure 10.2b, 10.5)

This value indicates an overall permeability reduction of 64%.

The P.B.D. treatment had removed the 1 mm seal at the surface which water flushing alone had previously been unable to do. However, the material permeability after P.B.D. treatment was lower than that of the material after rehabilitation by water flushing alone and prior to any P.B.D. treatment. This apparent reduction in permeability with P.B.D. treatment was also noted in tests 008 and 009. No logical explanation can be offered by the author.

When the sample was finally removed and inspected, only minor remaining evidence of the previously noted 1 mm thick surface layer could be found. The entire sample appeared to be homogeneous.

Material 3

Porosity = 38.2%

(original) Non-linear $K_o = 1/a = 450$ mm/min, $b/a^2 = .18$
(Table 10.1, Figures 10.3a, 10.5)

See Table 10.2 and Figure 10.8. With time of exposure there was a relatively minor decrease in the permeability of some portion of the sample between the exposed face and tapping 1. The final pressure drop across the 0 to 64 mm of the sample was only 3.5 metres of water.

Whole mud flowed freely from the sample for most of this test. The decrease in permeability in the top 64 mm of the sample reduced the mud flow rate through the sample from $2\frac{1}{2}$ litres/minute at $\frac{1}{2}$ minute to 0.8 litres/minute at 40 minutes.

When the sample was removed and inspected, the entire sample appeared homogeneous. There was no evidence of a thin cohesive seal at the sample face.

The sample was reinstalled. The test cell was washed clean of mud and filled with water. The sample was easily washed clean and flushing continued until no further improvement was noticeable.

The results of permeability testing after water flushing alone were;

(exposed) Non-linear $K_e = 1/a = 370$ mm/min, $b/a^2 = .25$
(Table 10.1, Figures 10.3b, 10.5)

There has been an overall reduction in the permeability of the entire sample.

After P.B.D. treatment and further flushing the material was again tested for permeability:

(exposed) Non-linear $K_e = 1/a = 390$ mm/min, $b/a^2 = .21$
(Table 10.1, Figures 10.3b, 10.5)

The P.B.D. treatment had further aided in rehabilitation of the damaged sample.

For materials with $b/a^2 > 0.1$, the reliability of extrapolating non-linear equations ($i = aV+bV^2$) as determined from only 3 points to a value of permeability $K = 1/a$ is very low. In such cases, estimates of damage may be more reliably evaluated by comparing the hydraulic gradients necessary to achieve specified flow velocities. For specified flow velocities between 2000 and 3000 mm/min, the indicated permeability reductions (Figure 10.5) for water flushing alone and P.B.D. treatment with final flushing were 40% and 30% respectively.

Considerable permanent damage had been done to the material by exposure to the mud. Water flushing alone was limited in its ability to remove damage to the sample. P.B.D. treatment followed by final flushing further aided rehabilitation of the sample but a resultant reduction in permeability of 30% was still present.

Final inspection of the sample revealed it to be visually homogeneous throughout its entire length.

Material 4

Porosity = 39.5%

(original) Non-linear $K_o = 1/a = 2000$ mm/min, $b/a^2 = 1.2$
(Table 10.1, Figures 10.4a, 10.5)

See Table 10.2 and Figure 10.9. This material was far more permeable than material 3 and as such no form of sealing was expected. However, after 2 minutes, there was a steady increase in the pressure drop between the exposed face and tapping 1. The final pressure drop of 7.7 metres of water across 0-64 mm was the largest reduction in pressure recorded for all materials in this test. It would seem that quite a large reduction in permeability had increasingly occurred with time in the top 64 mm of this material.

Whole mud flowed freely from the sample for the entire test duration. The decrease in permeability in the top 64 mm of the sample reduced the mud flow rate through the sample from 12 litres/min. at ½ minute to 5 litres/min. at 40 minutes. This final loss rate of mud was still very high.

This sample was not inspected. It is the author's opinion that it would have been similar to material 3, i.e. it would have appeared to be homogeneous without any distinct layer near the face of the sample.

The sample was very easily flushed clean when pressure was applied to water above the sample. Only limited flushing was necessary to achieve optimum rehabilitation of the sample.

The subsequent P.B.D. treatment and final water flushing achieved no further improvement in the flow behaviour of the damaged sample material. Results of permeability testing after P.B.D. treatment as presented in Table 10.1 have not been plotted in Figure 10.4b.

See Figure 10.5. For this material $b/a^2 > 0.1$ and the reliability of extrapolating the non-linear expression ($i = aV + bV^2$) as determined from only 3 points to a value of permeability $K = 1/a$ would be very low. In this case, an estimate of damage may be more reliably evaluated by comparing the hydraulic gradients necessary to achieve specified flow velocities between 4000 and 7000 mm/min. When this was done the estimated overall permanent reduction in permeability of the sample was 18%.

Permanent damage has been done to the material due to exposure to the mud. Water flushing alone was as effective as P.B.D. treatment in rehabilitating the sample to its final state in which a reduction of 18% in permeability had occurred.

Final inspection of the sample revealed it to be visually homogeneous throughout its entire length.

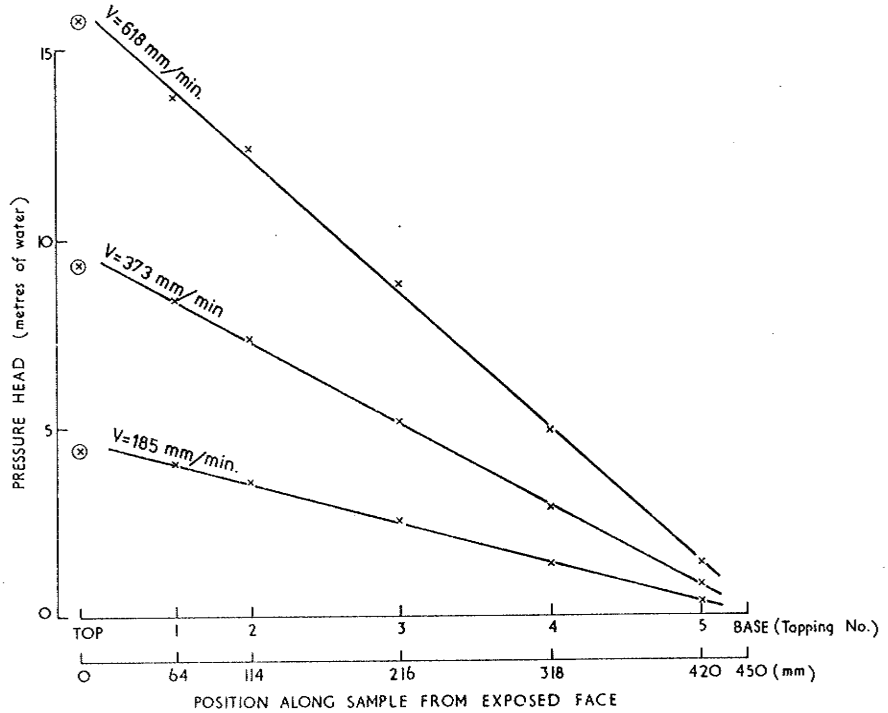


FIGURE 10·1(a) TEST 010 MATERIAL No.1.

Pressure Distributions Before Exposure to Drilling Mud.

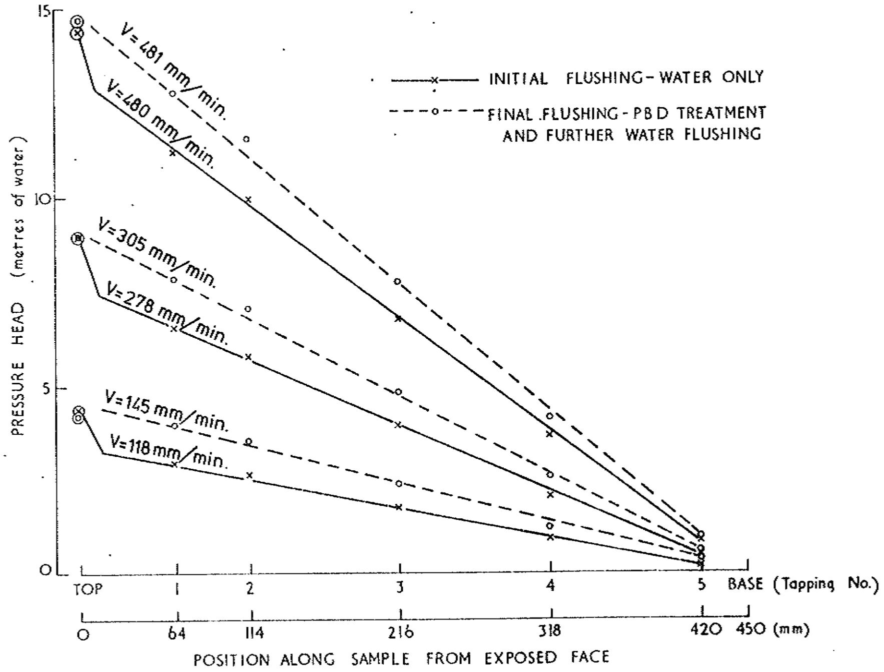


FIGURE 10·1 (b) TEST 010 MATERIAL No.1.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

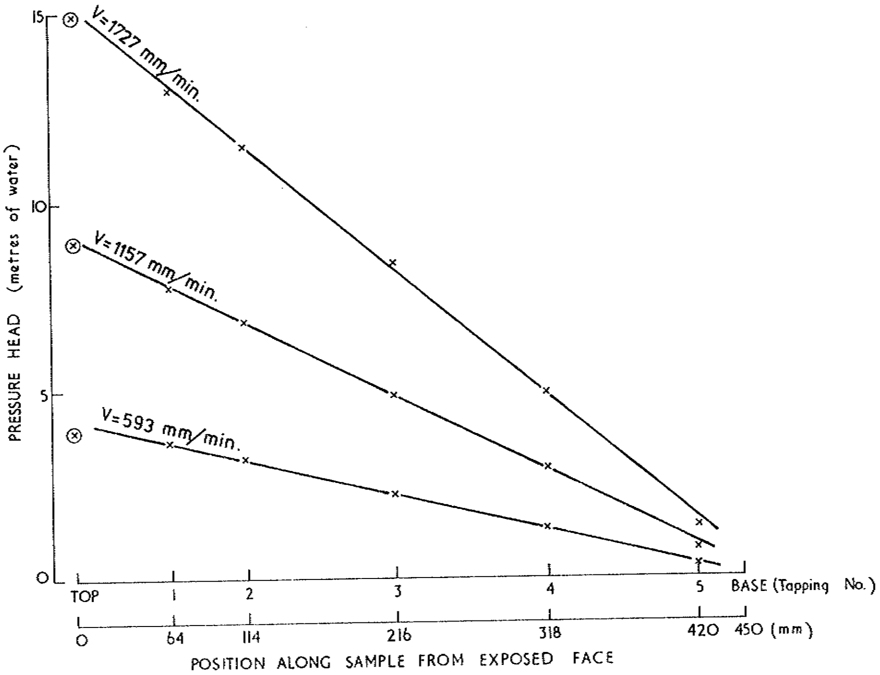


FIGURE 10·2 (a) TEST 010 MATERIAL No. 2.

Pressure Distributions Before Exposure to Drilling Mud.

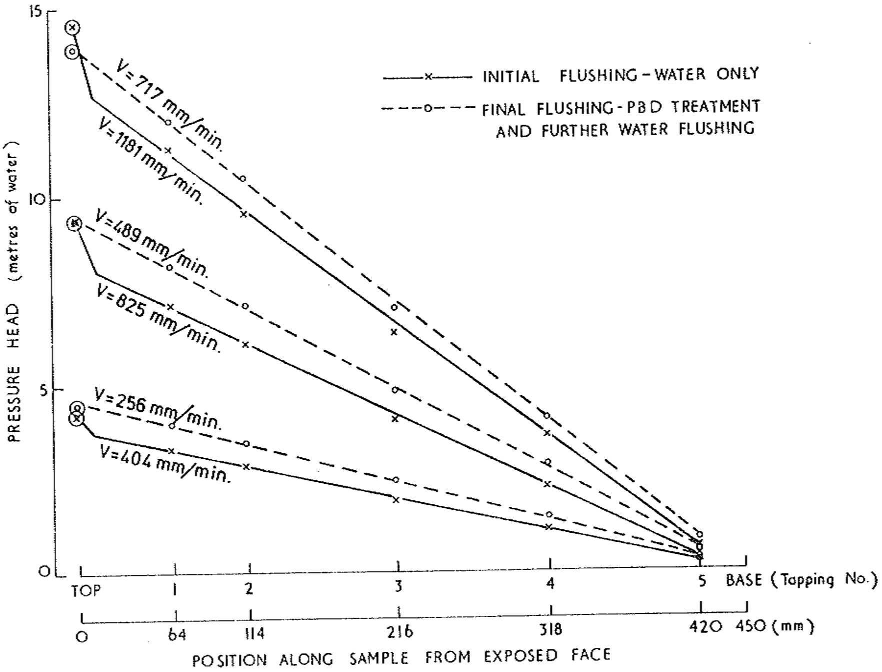


FIGURE 10·2 (b) TEST 010 MATERIAL No. 2.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

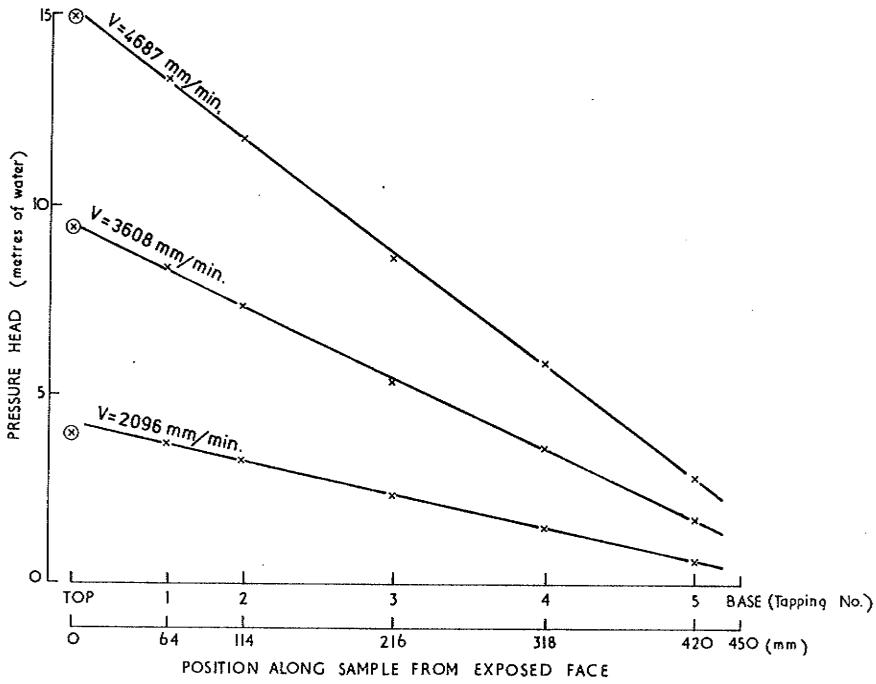


FIGURE 10·3(a) TEST 010 MATERIAL No.3.

Pressure Distributions Before Exposure to Drilling Mud.

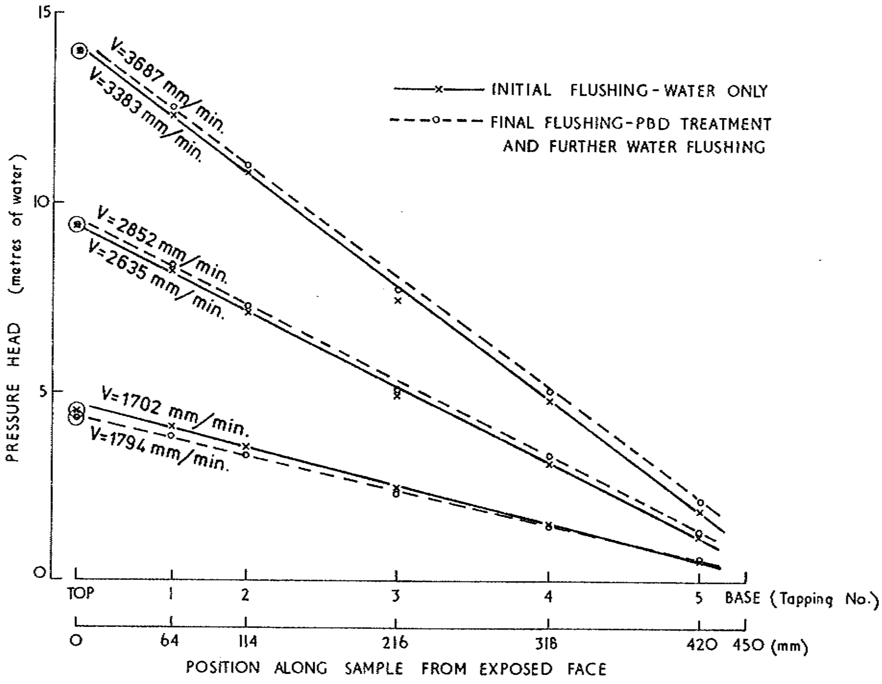


FIGURE 10·3 (b) TEST 010 MATERIAL No.3.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

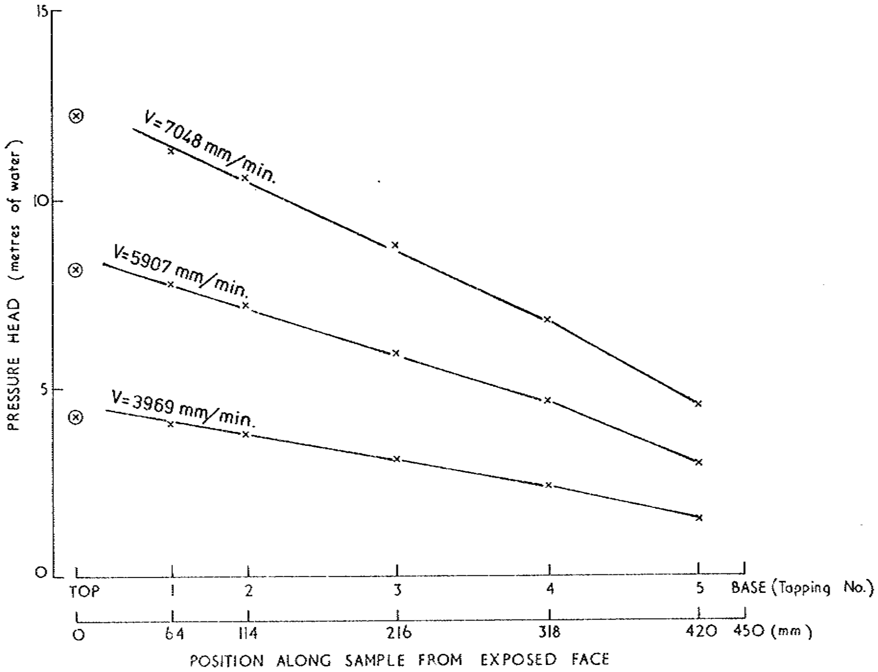


FIGURE 10·4(a) TEST 010 MATERIAL No.4.

Pressure Distributions Before Exposure to Drilling Mud.

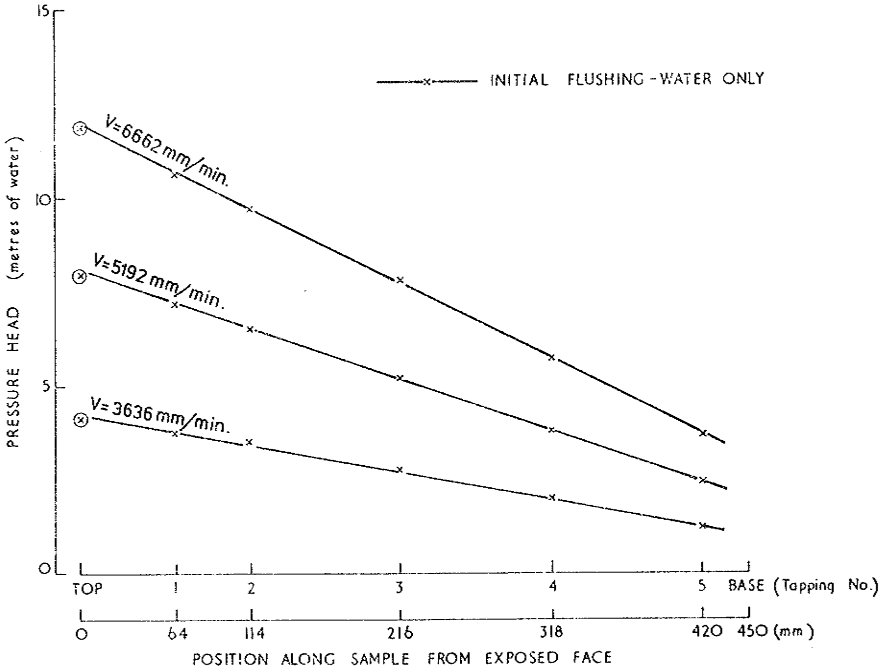
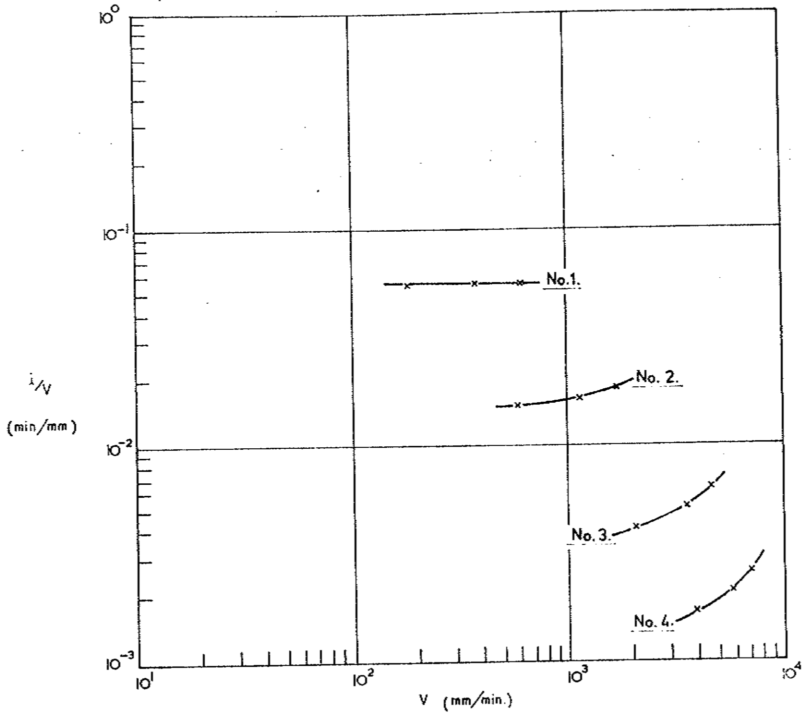
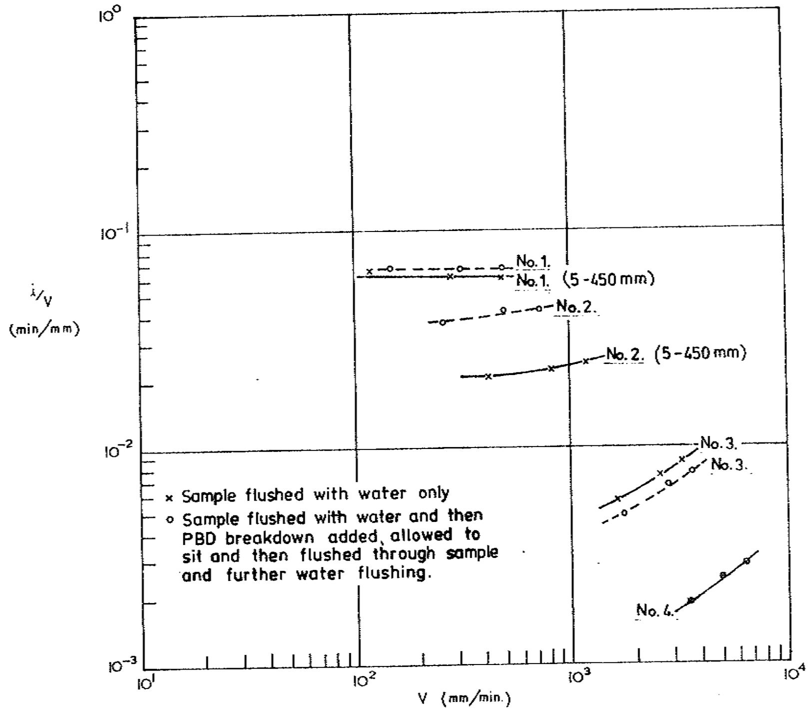


FIGURE 10·4(b) TEST 010 MATERIAL No.4.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.



(a) Before Exposure to Drilling Mud



(b) After Exposure to Drilling Mud

FIGURE 10·5 TEST 010

HYDRAULIC FLOW PROPERTIES OF TEST MATERIALS (i/V versus V)

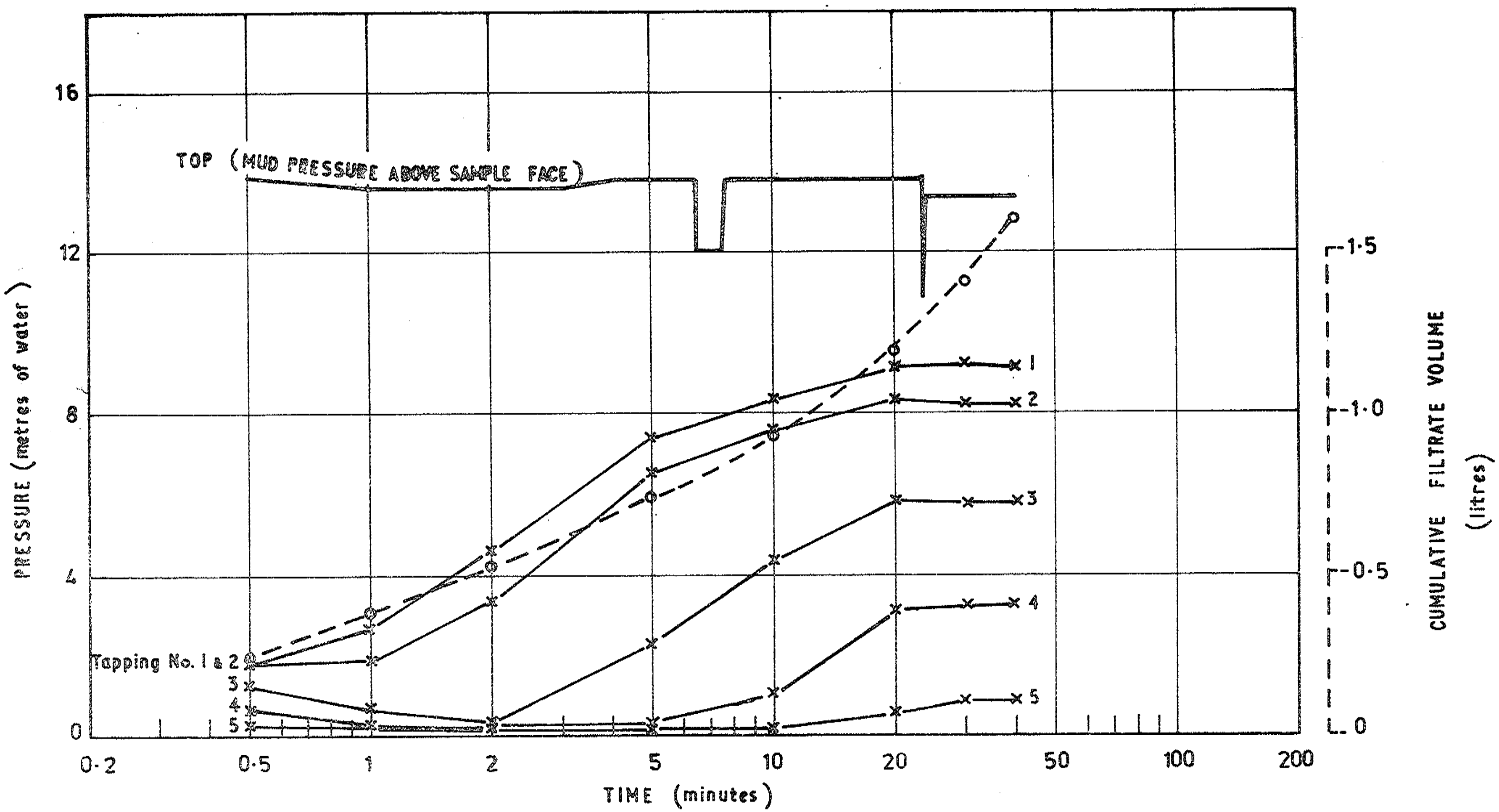


FIGURE 10·6 TEST 010 MATERIAL 1.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

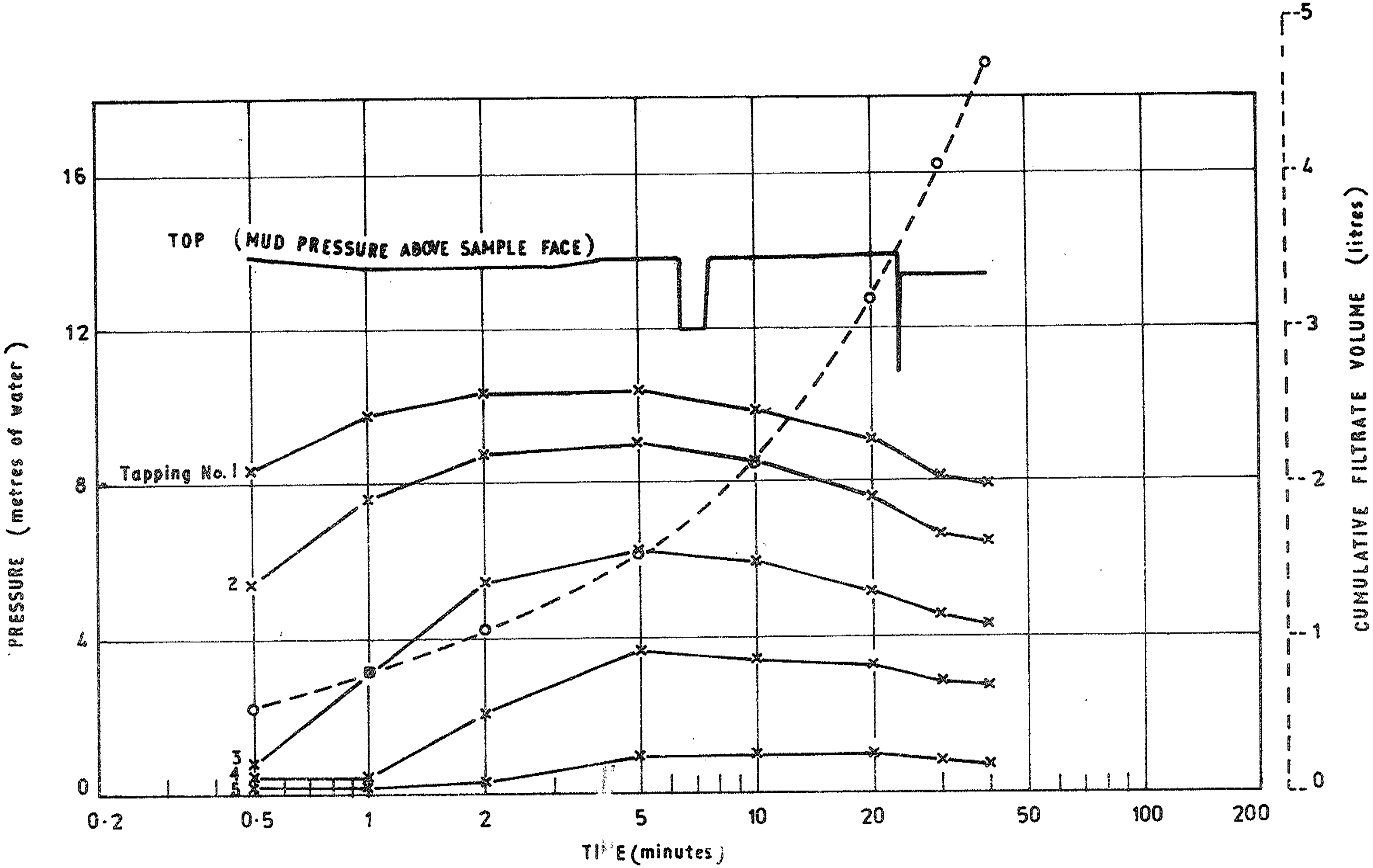


FIGURE 10·7 TEST 010 MATERIAL 2.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

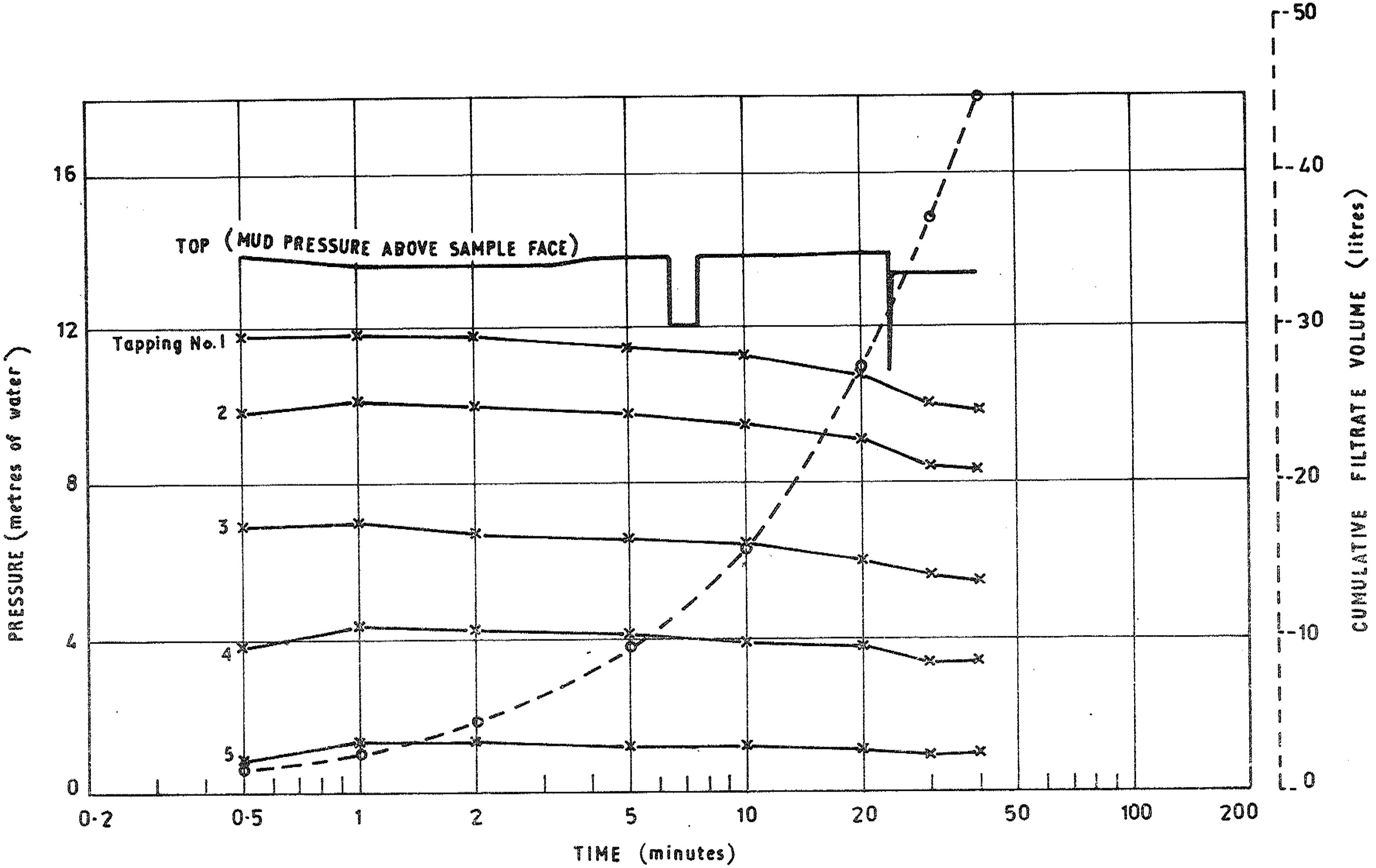


FIGURE 10·8 TEST 010 MATERIAL 3.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

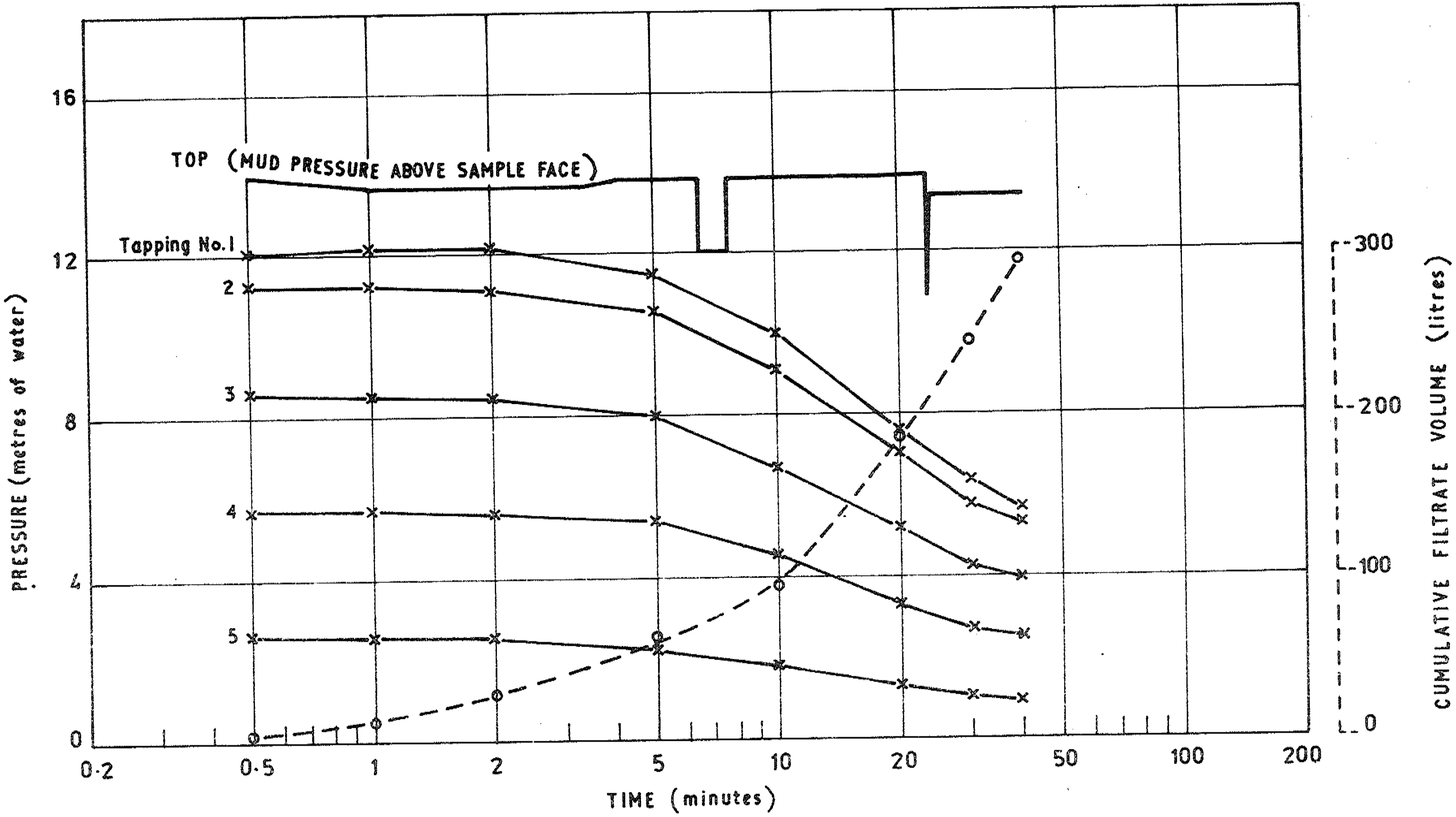


FIGURE 10·9 TEST 010 MATERIAL 4.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

Table 10.1 Test 010

Permeability testing of material samples.

Values of pressure (metres of water) as recorded at various positions along the sample for a measured flow of water through the sample.

Material	Flow Rate litres/ min.	Velocity mm/ min.	Tapping No. Top	1	2	3	4	5
			Position along sample from datum (mm)					
			0	64	114	216	318	420
Material Tests before Exposure to Drilling Mud								
1	3.97	618	15.82	13.74	12.41	8.76	4.92	1.39
	2.40	373	9.33	8.38	7.37	5.17	2.90	.82
	1.19	185	4.43	4.04	3.59	2.52	1.39	.38
2	11.11	1727	14.98	12.98	11.47	8.32	4.98	1.39
	7.44	1157	8.94	7.75	6.81	4.85	2.96	.76
	3.81	593	3.97	3.66	3.22	2.27	1.33	.32
3	30.15	4687	15.06	13.36	11.78	8.63	5.86	2.84
	23.21	3608	9.44	8.38	7.37	5.36	3.59	1.70
	13.48	2096	3.97	3.72	3.28	2.33	1.52	.63
4	45.34	7048	12.23	11.28	10.59	8.76	6.74	4.48
	38.00	5907	8.18	7.75	7.19	5.93	4.60	2.96
	25.53	3969	4.28	4.04	3.78	3.09	2.33	1.45
Material Tests after Exposure to Drilling Mud Initial Flushing - Water only								
1	3.09	480	14.37	11.15	9.89	6.68	3.59	.82
	1.79	278	8.94	6.49	5.74	3.85	2.02	.51
	.76	118	4.36	2.90	2.59	1.70	.89	.19
2	7.60	1181	14.45	11.15	9.45	6.24	3.53	.76
	5.31	825	9.33	7.06	5.99	3.91	2.21	.44
	2.60	404	4.20	3.28	2.78	1.83	1.07	.26
3	21.76	3383	13.91	12.29	10.78	7.37	4.73	1.83
	16.95	2635	9.33	8.13	7.06	4.85	3.03	1.14
	10.95	1702	4.51	4.04	3.53	2.40	1.45	.51
4	42.86	6662	11.85	10.59	9.64	7.75	5.67	3.66
	33.40	5192	7.95	7.12	6.49	5.17	3.78	2.40
	23.39	3636	4.09	3.72	3.41	2.71	1.96	1.20

Table 10.1 Test 010 (cont'd.)

Material	Flow Rate litres/ min.	Velocity mm/ min.	Tapping No.					
			Top	1	2	3	4	5
			Position along sample from datum (mm)					
			0	64	114	216	318	420
Material Tests after Exposure to Drilling Mud Final Flushing - P.B.D. Treatment and Further Water Flushing								
1	3.09	481	14.68	12.73	11.47	7.69	4.10	.95
	1.96	305	8.94	7.82	7.00	4.73	2.52	.57
	.94	145	4.20	3.91	3.47	2.33	1.20	.32
2	4.62	717	13.83	11.91	10.40	6.93	3.97	.82
	3.15	489	9.33	8.07	7.00	4.73	2.78	.63
	1.64	256	4.36	3.91	3.41	2.33	1.39	.32
3	23.72	3687	13.91	12.41	10.90	7.63	4.98	2.08
	18.35	2852	9.33	8.26	7.19	4.98	3.22	1.33
	11.54	1794	4.28	3.78	3.28	2.27	1.45	.57
4	42.35	6584	11.62	10.65	9.77	7.88	5.86	3.85
	34.16	5310	8.03	7.37	6.74	5.42	3.97	2.52
	23.67	3679	3.97	3.72	3.41	2.71	1.96	1.20

Table 10.2 Test 010

Sample behaviour during time of exposure to drilling mud.

Material	Time (minutes)	Filtrate Volume (litres)	Pressure (metres of water) Tapping No.					
			Top	1	2	3	4	5
			Position along sample from datum (mm)					
			0	64	114	216	318	420
1	½	.23	13.91	1.70	1.70	1.20	.57	.32
	1	.385	13.61	2.59	1.83	.57	.32	.19
	2	.525	13.61	4.48	3.34	.32	.32	.19
	5	.745	13.76	7.37	6.49	2.21	.32	.19
	10	.925	13.83	8.38	7.63	4.35	.95	.19
	20	1.195	13.91	9.14	8.38	5.86	3.09	.44
	22		13.91	9.26	8.51	5.93	3.22	.70
	30	1.41	13.45	9.26	8.13	5.74	3.22	.82
	40	1.60	13.45	9.14	8.13	5.74	3.22	.82
2	½	.545	13.91	8.38	5.48	.82	.44	.19
	1	.80	13.61	9.77	7.63	3.22	.44	.19
	2	1.06	13.61	10.40	8.76	5.48	2.08	.32
	5	1.54	13.76	10.40	9.01	6.24	3.72	.95
	10	2.11	13.83	9.89	8.51	5.99	3.47	.95
	20	3.19	13.91	9.14	7.63	5.23	3.34	.95
	23		13.91	8.95	7.50	5.11	3.09	.95
	30	4.05	13.45	8.13	6.74	4.60	2.84	.82
	40	4.71	13.45	8.00	6.49	4.35	2.71	.70
3	½	1.50	13.91	11.78	9.77	6.87	3.85	.95
	1	2.55	13.61	11.91	10.15	7.00	4.35	1.33
	2	4.55	13.61	11.78	10.02	6.74	4.22	1.33
	5	9.35	13.76	11.53	9.77	6.49	4.10	1.20
	10	15.80	13.83	11.28	9.52	6.37	3.85	1.20
	20	27.6	13.91	10.78	9.14	5.99	3.72	1.07
	23		13.91	10.71	8.95	5.86	3.59	1.01
	30	37.0	13.45	10.02	8.38	5.61	3.34	.95
	40	45.0	13.45	9.89	8.26	5.36	3.34	.95
4	½	6	13.91	12.04	11.28	8.63	5.74	2.59
	1	12	13.61	12.16	11.28	8.51	5.74	2.59
	2	30	13.61	12.16	11.15	8.51	5.61	2.46
	5	63	13.76	11.53	10.65	8.00	5.36	2.21
	10	96	13.83	10.02	9.14	6.74	4.48	1.83
	20	186	13.91	7.63	7.12	5.23	3.34	1.33
	24			7.31	6.56	4.79	3.09	1.20
	30	246	13.45	6.37	5.74	4.22	2.71	1.07
	40	296	13.45	5.74	5.36	3.97	2.46	.95

V11 Test 011: Results and Observations

The mud was made up as approximately 0.6% (6 lbs/100 gallons) by weight of Hydropol (new product) plus 6% by weight of a prepared sand, the grading of which is shown in Figure 1.1. The sand added was of similar grading to a sample of sand which was carried by the mud during rotary drilling of a typical hole in unconsolidated sediments in New South Wales.

The mud was circulated for 1½ hours prior to starting the test. The sand appeared to settle quite quickly in the mud bin. However, since the offtake to the pump was at the base of the bin, sand was circulated in suspension with the mud. When testing the sand content, the sample was taken from the return inlet to the mud bin.

The mud properties were tested both before and during the exposure of the sample materials to the mud. The mud was maintained as follows for the duration of the test.

Temperature = 24°C
Specific gravity = 1.04
Marsh Funnel Viscosity = 52 seconds
A.P.I. Filter Press (½ area)
  Initial spurt ($V_s + V_x$) = 15 cc
  Corrected volume (V_c) = 5 cc
Filter cake thickness = 1/32" (sand grains)
Sand content = 1½% by volume
Plastic viscosity = 13.5 cps
Yield point = 20 lb/100 sq. ft.

During the exposure time of 2 hours, both the mud flow pressure and velocity varied considerably about the target values of 20 psi (14 metres of water) and 120 ft/min. respectively (Figure 11.1). Considerable surging of both pressure and velocity was due to periods of cavitation occurring in the pump which had undergone maintenance since the completion of test 010.

After the 120 minutes of pressurised mud flow the pump was turned off and the test cell was isolated. The pressure was relieved and the mud was left to stand (static flow condition) above the samples for 24 hours.

All mud was drained from above the samples which were removed, inspected and reinstalled.

The test cell was filled with water and the samples left under water (no pressure) for 17 hours.

Each material was then flushed through under applied pressures up to 20 psi until no further improvement in flow could be obtained.

Each sample material was retested for permeability.

Romud P.B.D. in the recommended concentration of 0.75 lb/100 gallons was added to the test apparatus.

After 4 hours, fluid was flushed through each material until the pH change indicated that P.B.D. solution was present throughout the sample length. Each sample was left as such for 30 minutes before further flushing was carried out to achieve optimum rehabilitation.

The samples were then retested for permeability to estimate the extent of permanent damage caused by exposure to the mud system.

The samples were left covered with water for 17 hours before being finally removed and inspected.

Material 1

Porosity = 38%

(original) Linear K_o = 15 mm/min

(Table 11.1, Figures 11.2a, 11.6)

See Table 11.2 and Figure 11.7. Within $\frac{1}{2}$ minute of exposure a seal formed somewhere in the top 64 mm of the sample. For the duration of the test this seal accounted for a pressure drop across the top 64mm of the material of approximately 7 to 8 metres of water head.

The mud filtrate loss rate decreased in time and was less than 2 cc/minute after 60 minutes of exposure. The total collected filtrate volume of .99 litres indicates an estimated depth of invasion of mud fluid of 405 mm into the sample.

The results of this test may be compared with test 010 wherein the same Hydropol concentration was used to make a pure mud with no sand contamination. The sandy mud used here produced a far more effective seal than the pure mud of test 010 where mud penetrated the entire sample after only 15 minutes.

The seal formed was still not as effective as those formed previously in tests using straight bentonite mud systems. (e.g. Test 002- $6\frac{1}{2}$% Aquagel - 20 psi - 120 ft/min. flow - a seal formed in top 10mm within 1 minute which prevented any loss of filtrate beyond .235 litres).

When the sample was removed and inspected, there was a build-up of low permeability cakey material approximately 10mm above the initial exposed face of the material. This cake layer was cohesive, quite plastic and contained considerable quantities of the sand added as a mud contaminant. The lower portion of the test cell had quantities of sand and mud lying in it. However, the cake build-up above the sample was firmly attached to the sample and was considered to be formed during the mud circulation period.

The cakey layer was disturbed by removing approximately one square inch before the sample was remounted on the test cell. There was no evidence of any internal sealing layer below the original sample surface.

After being left under water for 17 hours, the material was quite readily flushed through with water under low pressures. This was expected since the cake build-up layer had been broken during inspection. Flushing was continued under a pressure of 20 psi until no further improvement was noted.

The results of permeability testing after water flushing alone were:

(exposed) Linear K_e = 12 mm/min.
(Table 11.1, Figures 11.2b, 11.6)

Virtually no evidence of any seal at the surface is shown in Figure 11.2b. An overall permeability reduction of 20% has occurred over the sample material beyond the surface cake seal which had been deliberately broken during inspection.

After P.B.D. treatment and further water flushing the material was again tested for permeability.

(exposed) 0-216 mm Linear K_e = 10 mm/min
216-450 mm Linear K_e - 13 mm/min
(Table 11.1, Figures 11.2b, 11.6)

The indicated permeability reductions were 33% and 13% for the 0-216 mm and 216-450 mm layers. If averaged over the entire sample length the damage would be of the order of 23%.

Thus the P.B.D. treatment has achieved very little improvement over straight water flushing in rehabilitating the material invaded by the mud but beyond the actual wall cake seal.

When the sample was finally removed and inspected only patchy remnants of a thick plastic cake seal were found above the face of the sample. The remainder of the material appeared to be homogeneous.

V11.4

Material 2

Porosity = 39%

(original) Non-linear K_o = $1/a = 46$ mm/min, $b/a^2 = .022$
(Table 11.1, Figures 11.3a, 11.6)

This sample of material 2 exhibited a far lower K_o than the previous tests.

See Table 11.2 and Figure 11.8. There was evidence of the formation of a seal somewhere above tapping 1 during the test exposure time. By the end of the test the seal was quite effective, accounting for a pressure drop of 9½ metres of water head over the top 64 mm of the sample.

The mud filtrate loss rate decreased in time and was less than 2 cc/minute after 80 minutes of exposure. Mud filtrate would have penetrated the entire sample length after 40 minutes when the collected filtrate volume was 1.10 litres. The total collected volume was 1.31 litres.

The results of this test may be compared with test 010. The sandy mud used here produced a reasonably effective seal whilst the pure Hydropol mud of test 010 did not effect much of a seal and mud penetrated the entire sample after only 4½ minutes.

The seal formed was still not as effective as those formed previously in tests using a straight bentonite mud system (tests 002, 003, 004) wherein the 10 mm thick internal seals formed within ½ minute prevented any further losses of filtrate.

When the sample was removed and inspected, there was a buildup of low permeability cakey material approximately 10 mm above the initial exposed face of the material. This cake layer was cohesive, quite plastic and contained considerable quantities of the mud contaminant sand. The lower portion of the test cell had quantities of sand and mud lying in it. However, the cake build-up above the sample was firmly attached to the sample and was considered to be formed during the mud circulation period.

The cakey layer was disturbed by removing approximately one square inch before the sample was remounted on the test cell. There was no evidence of any internal sealing below the sample surface. The remainder of the sample was visually homogeneous.

After being left under water for 17 hours the material was quite readily flushed through with water under low pressures. This was expected since the builtup sealing cake had been broken during inspection. Flushing was continued under a pressure of 20 psi until no further improvement was noted.

The sample was then removed and inspected again. The built-up cakey layer was gone. Also the top 10 mm of the sample had been removed. It is the author's opinion that the entire cake build-up layer was removed en masse (taking the 10 mm of material below the sample face with it) when the test cell was being filled with water after the previous inspection. The cake layer when originally inspected was seen to be quite plastic and could be expected to remain as a cohesive entity whether above or removed from the sample.

The sample was replaced and further water flushing carried out before permeability testing the material.

(exposed) 0-318 mm Non-linear $K_e = 1/a = 32$ mm/min, $b/a^2 = .013$
318-450 mm Non-linear $K_e = 1/a = 39$ mm/min, $b/a^2 = .013$
(Table 11.1, Figures 11.3b, 11.6)

There was no evidence of any seal above tapping 1. There was graded damage resulting in permeability reductions of 30% and 15% for the 0-318 mm and 318-450 mm portions of the material.

After P.B.D. treatment and further water flushing the material was again tested for permeability.

(exposed) 0-318 mm Non-linear $K_e = 1/a = 27$ mm/min, $b/a^2 = .008$
318-450 mm Non-linear $K_e = 1/a = 39$ mm/min, $b/a^2 = .013$
(Table 11.1, Figures 11.3b, 11.6)

The P.B.D. treatment had achieved no further improvement over water flushing in the 318-450 mm layer which still showed damage of 15%. The material permeability of the 0-318 mm layer after P.B.D. treatment was lower than after water flushing alone and prior to any P.B.D. treatment. The final reduction in permeability in this 0-318 mm layer was 41%.

This apparent damage caused by the P.B.D. treatment was also noted in all other tests using Hydropol mud. No explanation can be offered by the author.

When the sample was finally removed and inspected, it appeared to be homogeneous throughout. As previously noted, the top 10 mm of the sample was missing.

Material 3

Porosity = 38.5%

(original) Non-linear $K_o = 1/a = 420$ mm/min, $b/a^2 = .13$
(Table 11.1, Figures 11.4a, 11.6)

See Table 11.2 and Figure 11.9. With time of exposure there was distinct evidence of the formation of a sealing layer somewhere above tapping 1. This seal was quite effective by the end of the test, accounting for a pressure drop of 10 metres of water head over the top 64mm of the sample.

The mud filtrate loss rate decreased with time of exposure and was 5 cc/min. at the end of the test when the total collected filtrate volume was 12.8 litres. Mud would have penetrated the entire sample length in the first 1 minute of exposure.

The results of this test may be compared with test 010. The sandy mud used here produced quite an effective seal whilst only minor sealing occurred using the pure Hydropol mud of test 010.

The seal, once developed (in this test), was not as effective in reducing further water loss as those seals formed with pure bentonite muds in tests 003 and 004. However, the total filtrate volumes collected in tests 003 and 004 were greater than the 12.8 litres passed in this test.

A sand contaminated bentonite mud (tests 005 and 006) formed very effective internal seals within the top 10 mm of the material within $\frac{1}{2}$ minute. These seals prevented any further loss of filtrate.

When the sample was removed and inspected a distinct 2-3mm thick internal sealing layer was evident in the top of the material. This layer was plastic, cohesive and contained sand from the mud. There was no external cake build-up above the sample face. The remainder of the sample beyond the top 5 mm appeared to be homogeneous.

After being left under water for 17 hours the material could be flushed through with water under pressure. However, the behaviour with continued flushing was quite extraordinary. The pressure drop across the top 64 mm of the sample was used as a measure of the effectiveness of the 2-3mm thick seal which was found at the top of the sample.

The seal appeared to be in an unstable condition. As flushing continued under a pressure of 20 psi the seal underwent cyclic changes of reforming and breaking down.

Consistent permeability test results were, however, readily obtained for the remainder of the sample beyond the sealing layer.

Subsequent P.B.D. treatment and further water flushing did nothing to alter the behaviour of both the sealing layer and the remainder of the sample. Water flushing alone was as effective as P.B.D. treatment in rehabilitation of the sample.

The results of permeability testing after water flushing alone and

P.B.D. treatment for the material beyond the seal were:-

(exposed) 10-216 mm Non-linear K_e = 1/a = 340 mm/min, b/a^2 = .16
216-450 mm Non-linear K_e = 1/a = 420 mm/min, b/a^2 = .19
(Table 11.a, Figure 11.4b, 11.6)

Apparently the damage done to the material had occurred in a step graded fashion.

For materials with $b/a^2 > 0.1$ the reliability of extrapolating non-linear equations ($i = aV + bV^2$) as determined from only 3 points to a value of permeability K = 1/a is very low. In this case a more reliable estimate of damage was evaluated by comparing the hydraulic gradients necessary to achieve flow velocities between 2000 and 3000 mm/min. Indicated reductions in permeability for the 10-216 mm and 216-450 mm layers were 35% and 18% respectively (Figure 11.6).

When the sample was finally removed and inspected, remnants of the 2-3mm internal seal were evident in patches over approximately 80% of the surface area of the sample. The remainder of the material appeared homogeneous.

Material 4

Porosity = 39%

(original) Non-linear K_o = 1/a = 7500 mm/min, b/a^2 = 18
(Table 11.1, Figures 11.5a, 11.6)

Due to the high non-linearity indicated by permeability testing of this original sample, the value of K_o = 1/a = 7500 mm/min. could be seriously in error.

See Table 11.2 and Figure 11.10. With time of exposure there was quite an effective seal formed somewhere above tapping 1. By the end of the test this seal effectively accounted for a pressure drop of 10.6 metres of water head which was almost the total drop across the entire sample length.

The mud filtrate loss rate decreased from an initial value of approximately 4 litres/min. to only 5 cc/min. at the end of the test when the total collected filtrate volume was 28.8 litres. Whole mud would have penetrated the entire sample length within the first ½ minute of exposure.

The sand contaminated mud used here produced an effective seal which is in direct contrast to the results of test 010 using a pure Hydropol mud. In test 010 no seal was developed and a total of 296 litres flowed through the sample in 40 minutes.

In test 003 using a pure bentonite mud no seal was developed.

Very effective internal seals were formed in both tests 005 and 006 using sand contaminated bentonite mud systems. The seals developed within the top 10 mm of the samples within $\frac{1}{2}$ minute of exposure and were so effective as to prevent any further losses of filtrate beyond 0.8 and 1 litre for tests 005 and 006 respectively.

These seals were far more effective than the one developed in this test using the sand contaminated Hydropol mud.

When the sample was removed and inspected a distinct 2-3 mm thick internal sealing layer was evident in the top of the material. This layer was plastic, cohesive and contained sand from the mud. There were a few small patches of the seal which appeared more permeable than the whole. There was no external cake build-up above the sample face nor evidence of mud and sand in the test cell. The remainder of the sample beyond the top 5 mm appeared to be homogeneous.

After being left under water for 17 hours the material was easily flushed clean when pressure was applied. Only limited flushing was necessary to achieve optimum rehabilitation of the sample.

The results of permeability testing after water flushing alone were:-

(exposed) 10-114 mm Non-linear $K_e = 1/a = 1400$ mm/min., $b/a^2 = 1.4$
114-450 mm Non-linear $K_e = 1/a = 1400$ mm/min., $b/a^2 = 0.8$
(Table 11.1, Figures 11.5b, 11.6)

As shown in Figure 11.5b only a small trace of the 2-3 mm seal formed in the top of the sample remained.

The subsequent P.B.D. treatment and final water flushing removed all trace of the sealing layer. However, no further flow improvement was obtained for the remainder of the material beyond the seal.

For this material $b/a^2 > 0.1$ and the reliability of extrapolating the non-linear expression ($i = aV + bV^2$) as determined from only 3 points to a value of permeability $K = 1/a$ would be very low. In this case, an estimate of damage was more reliably evaluated by comparing the hydraulic gradients necessary to achieve specified flow velocities of the order of 4000 to 6000 mm/min. When this was done (Figure 11.6) the estimated permanent reductions in permeability for the 10-114 mm and 114-450 mm layers were 60% and 43% respectively.

Final inspection of the material revealed only very small traces of the distinct 2-3 mm internal seal previously noted as being formed during mud exposure. The remainder of the sample was visually homogeneous.

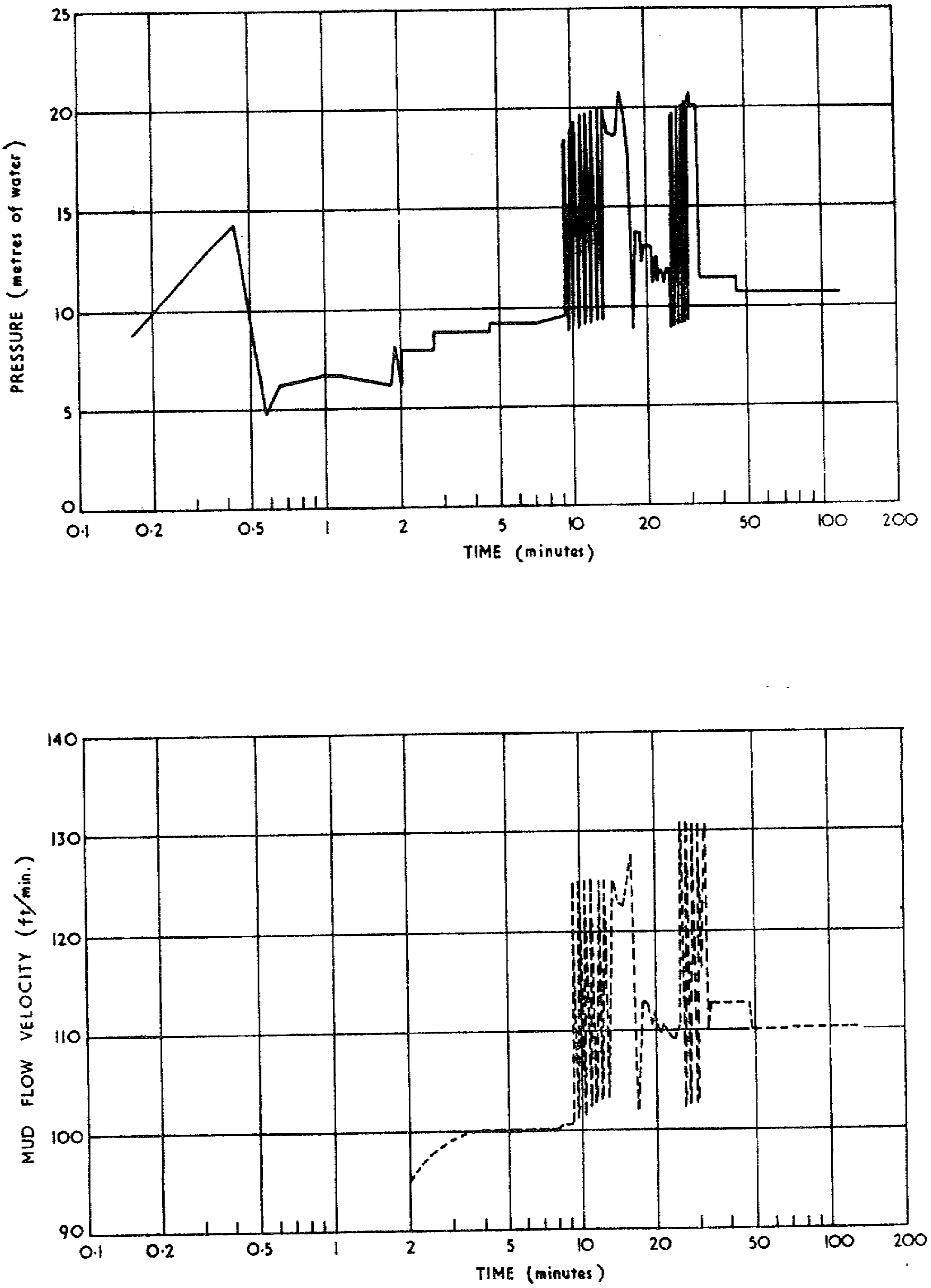


FIGURE 11·1 TEST 011

MUD FLOW PRESSURE AND VELOCITY VARIATIONS DURING TIME OF EXPOSURE

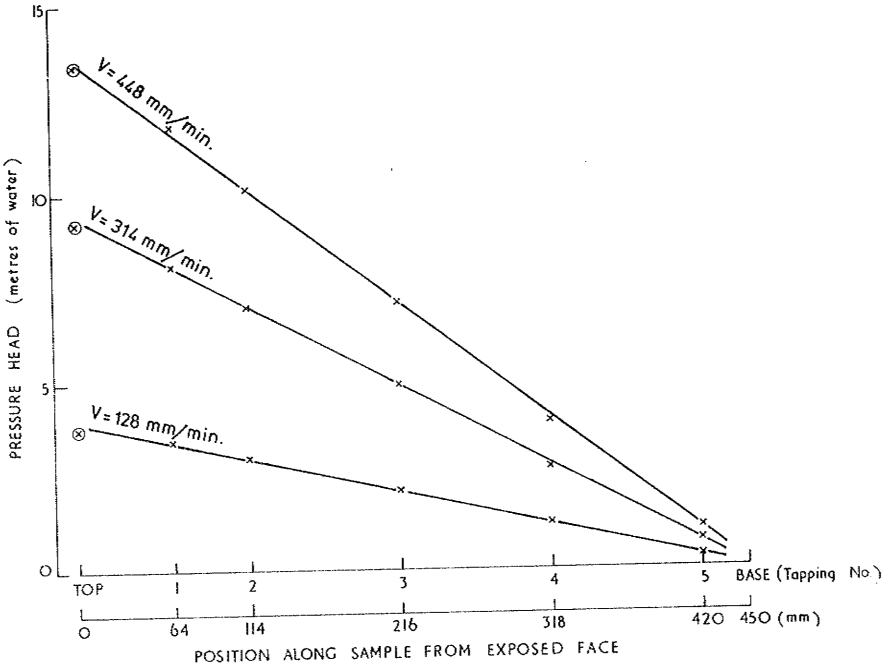


FIGURE 11·2 (a)   TEST 011   MATERIAL No. 1.

Pressure Distributions Before Exposure to Drilling Mud.

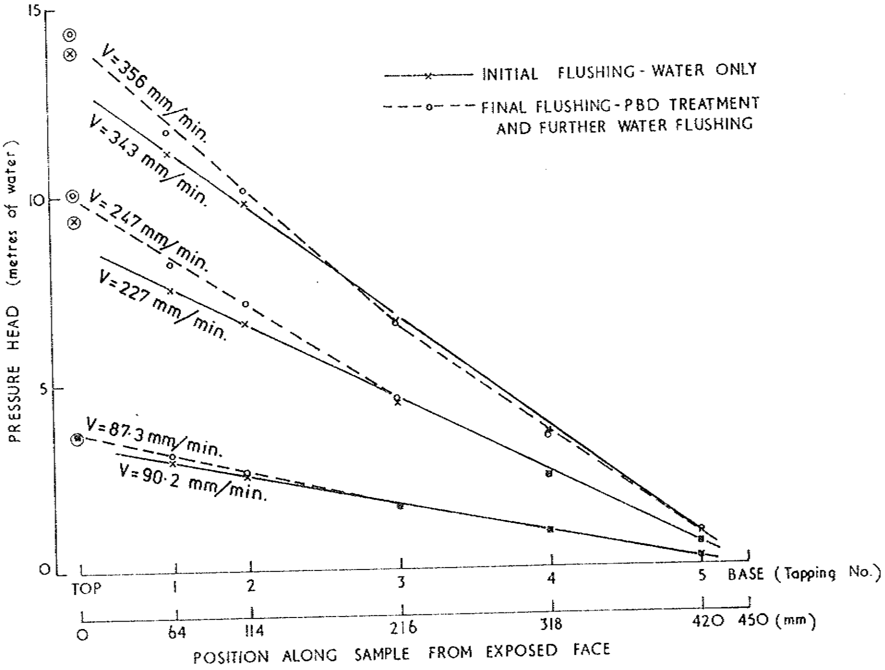


FIGURE 11·2 (b)   TEST 011   MATERIAL No. 1.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

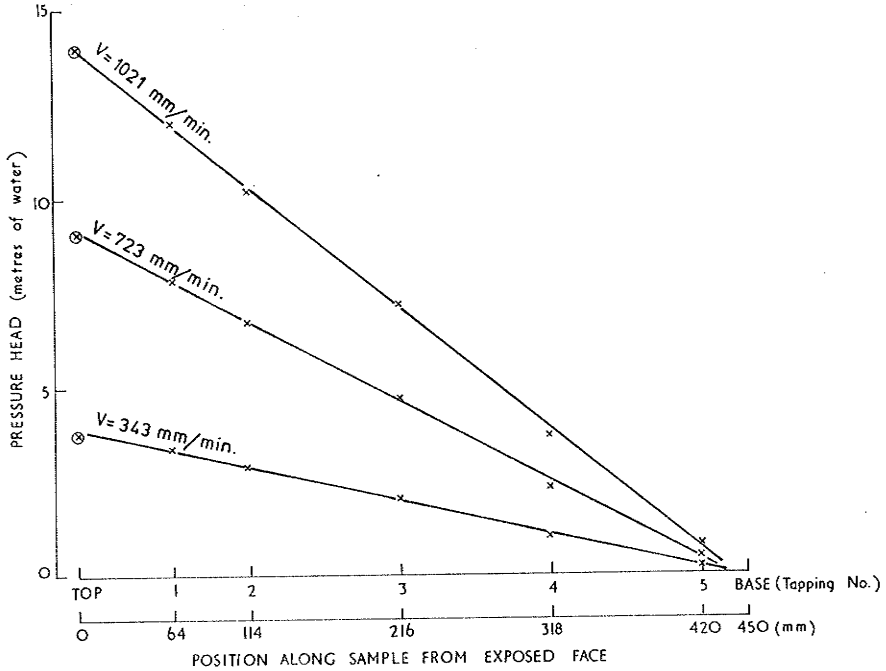


FIGURE 11·3 (a) TEST 011 MATERIAL No. 2.

Pressure Distributions Before Exposure to Drilling Mud.

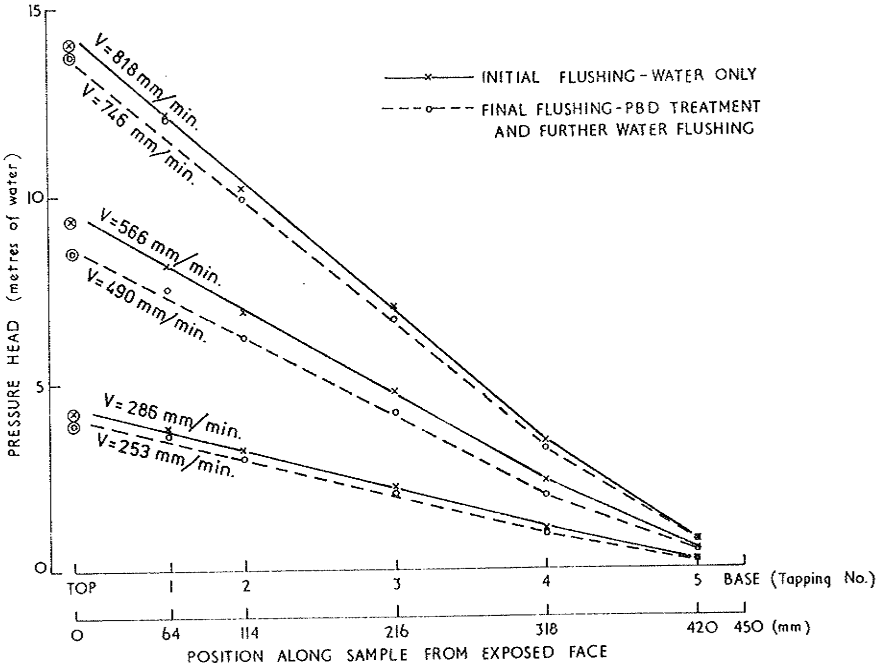


FIGURE 11·3 (b) TEST 011 MATERIAL No. 2.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

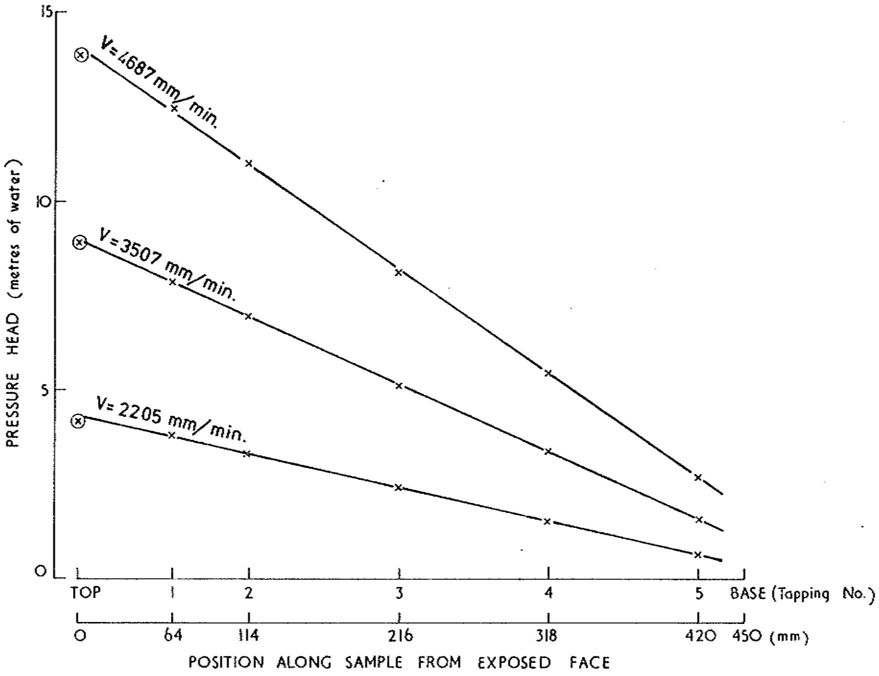


FIGURE 11·4 (a) TEST 011 MATERIAL No. 3.

Pressure Distributions Before Exposure to Drilling Mud.

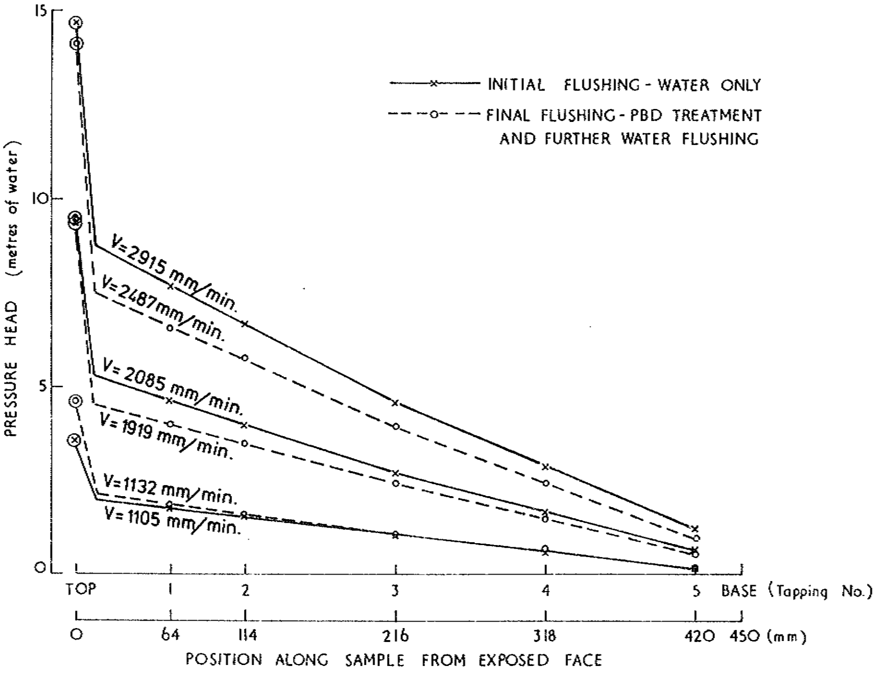


FIGURE 11·4 (b) TEST 011 MATERIAL No. 3.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.

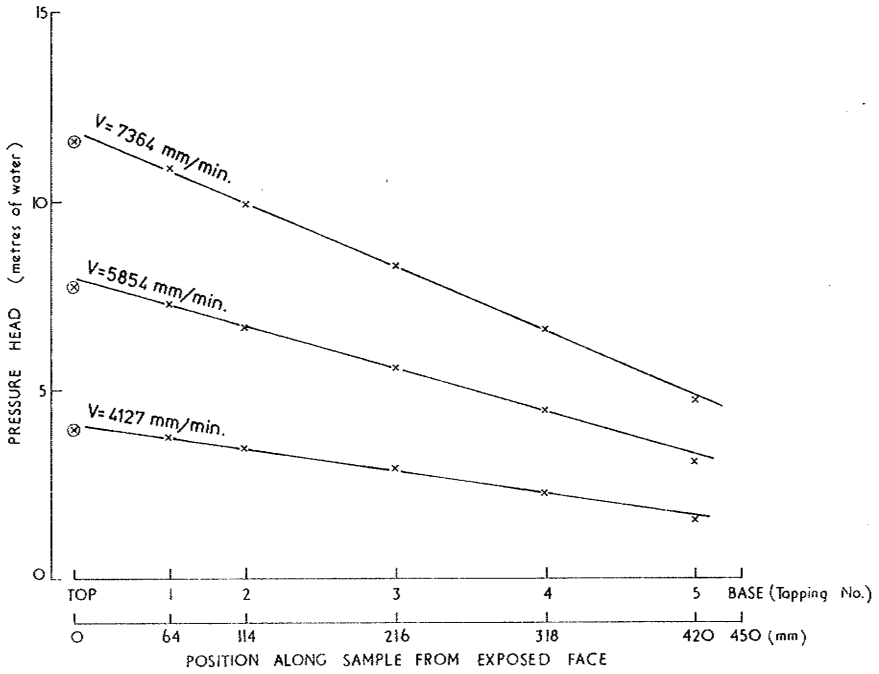


FIGURE 11·5 (a) TEST 011 MATERIAL No. 4.

Pressure Distributions Before Exposure to Drilling Mud.

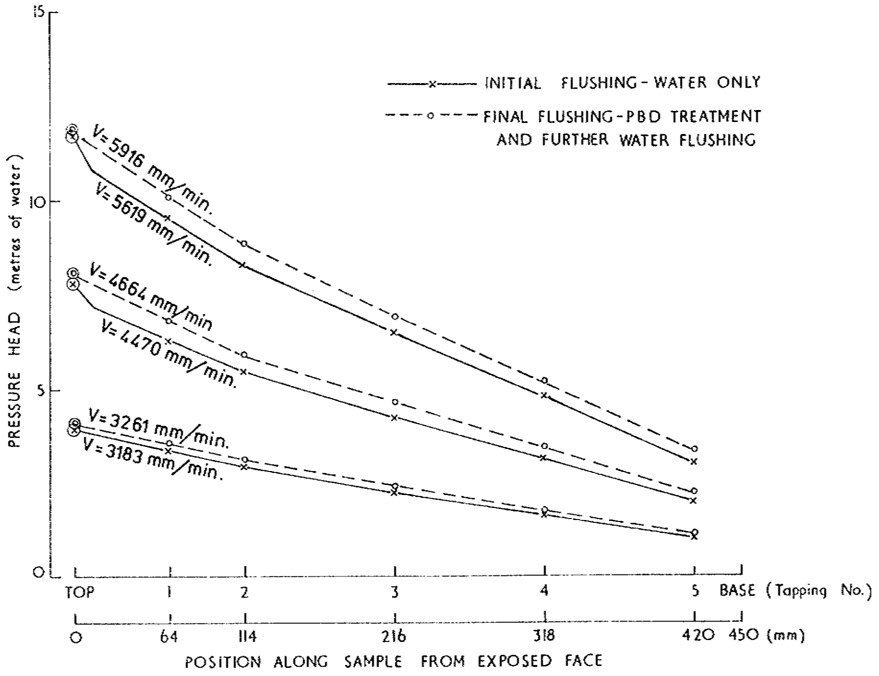
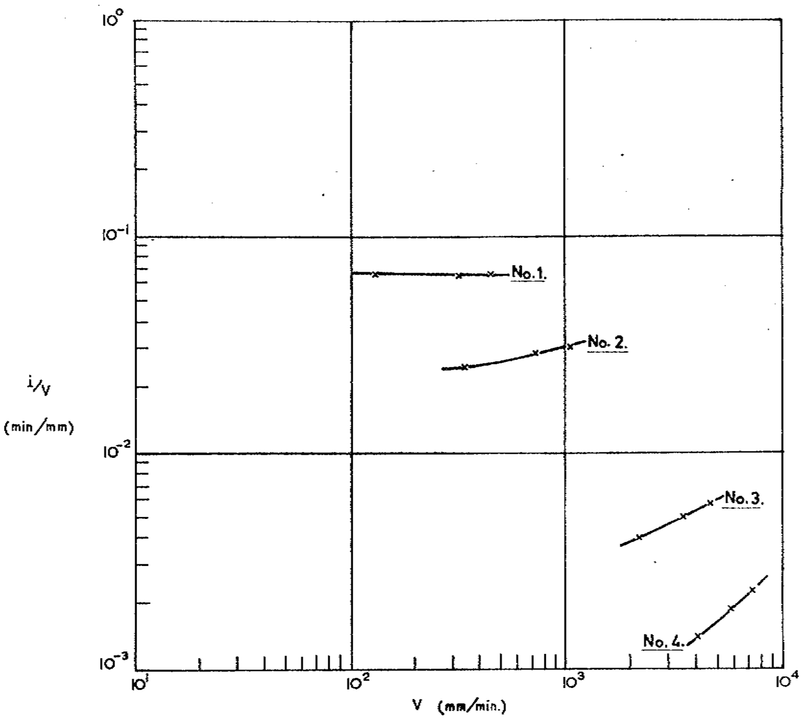
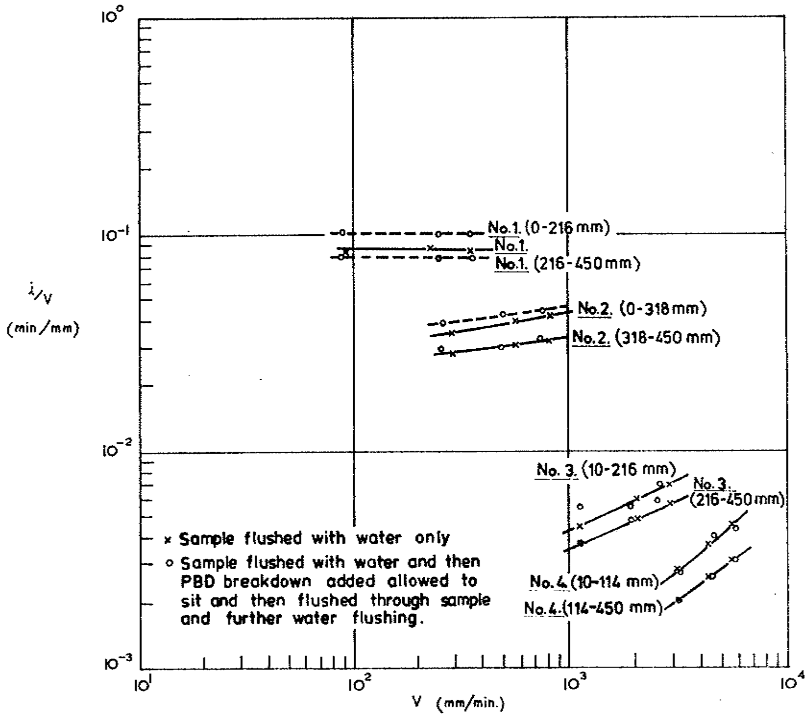


FIGURE 11·5 (b) TEST 011 MATERIAL No. 4.

Pressure Distributions After Exposure to Drilling Mud and Subsequent Flushing.



(a) Before Exposure to Drilling Mud



(b) After Exposure to Drilling Mud

FIGURE 11·6 TEST 011

HYDRAULIC FLOW PROPERTIES OF TEST MATERIALS (i/V versus V)

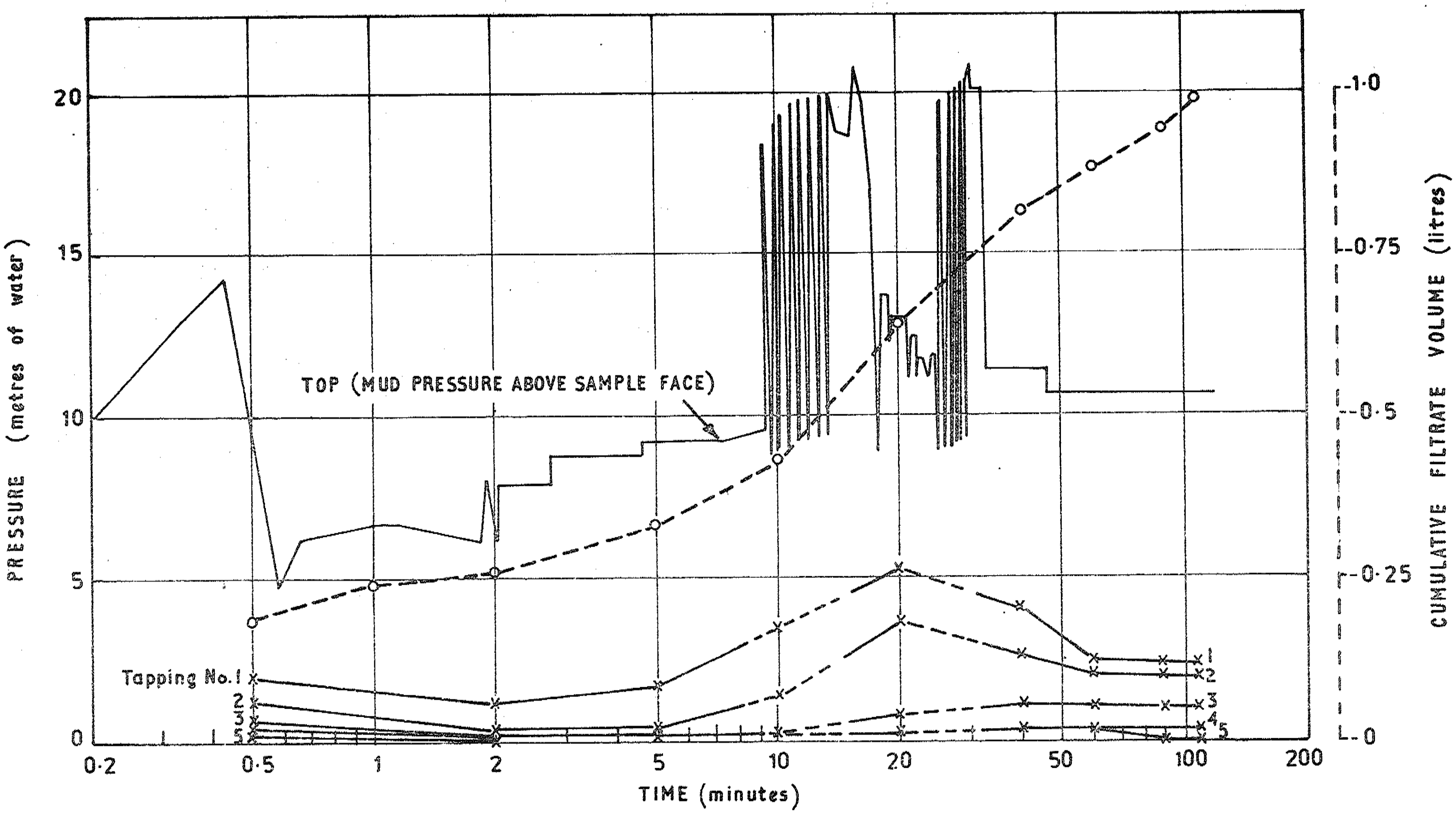


FIGURE 11·7

TEST 011

MATERIAL 1.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

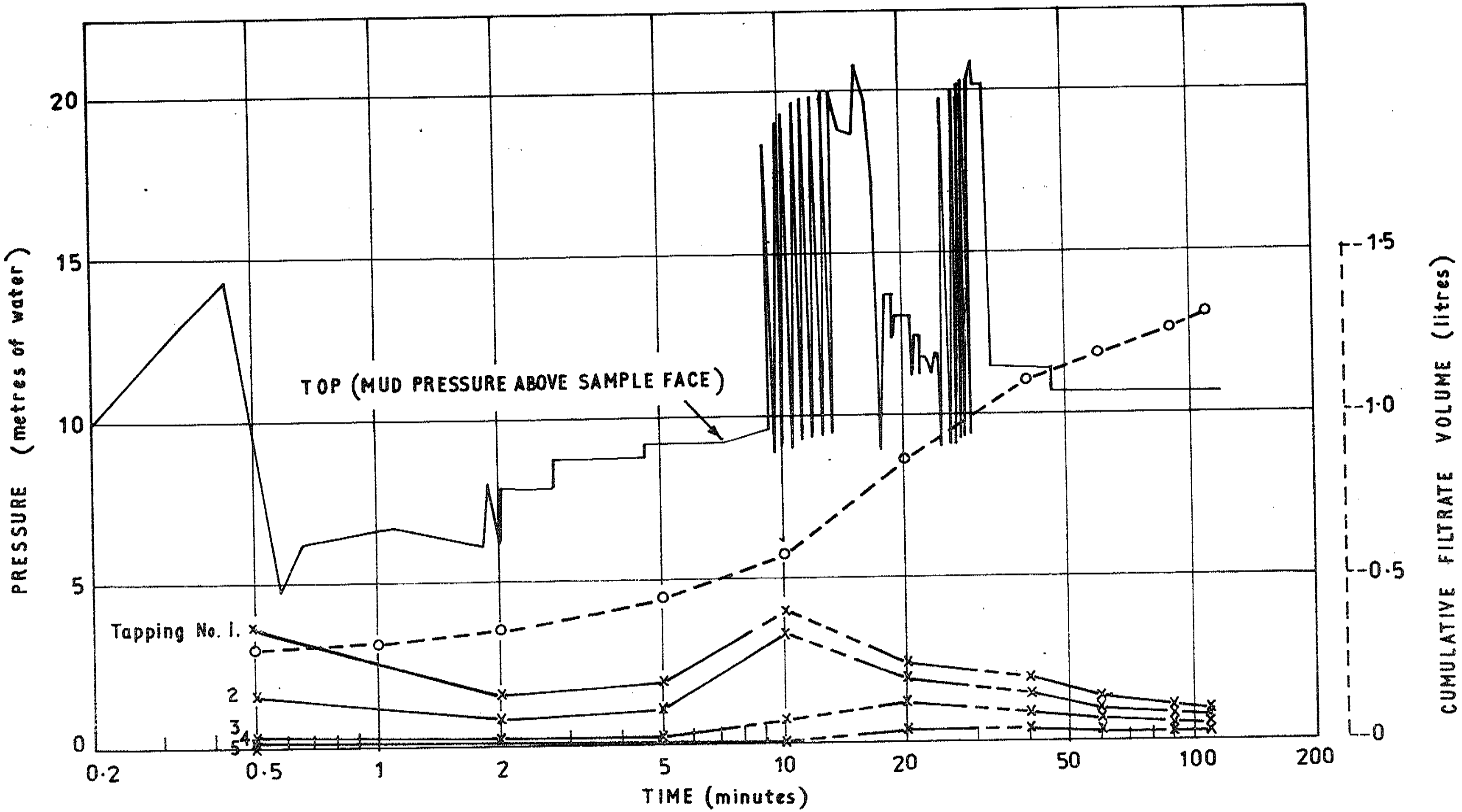


FIGURE 11·8 TEST 011 MATERIAL 2.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

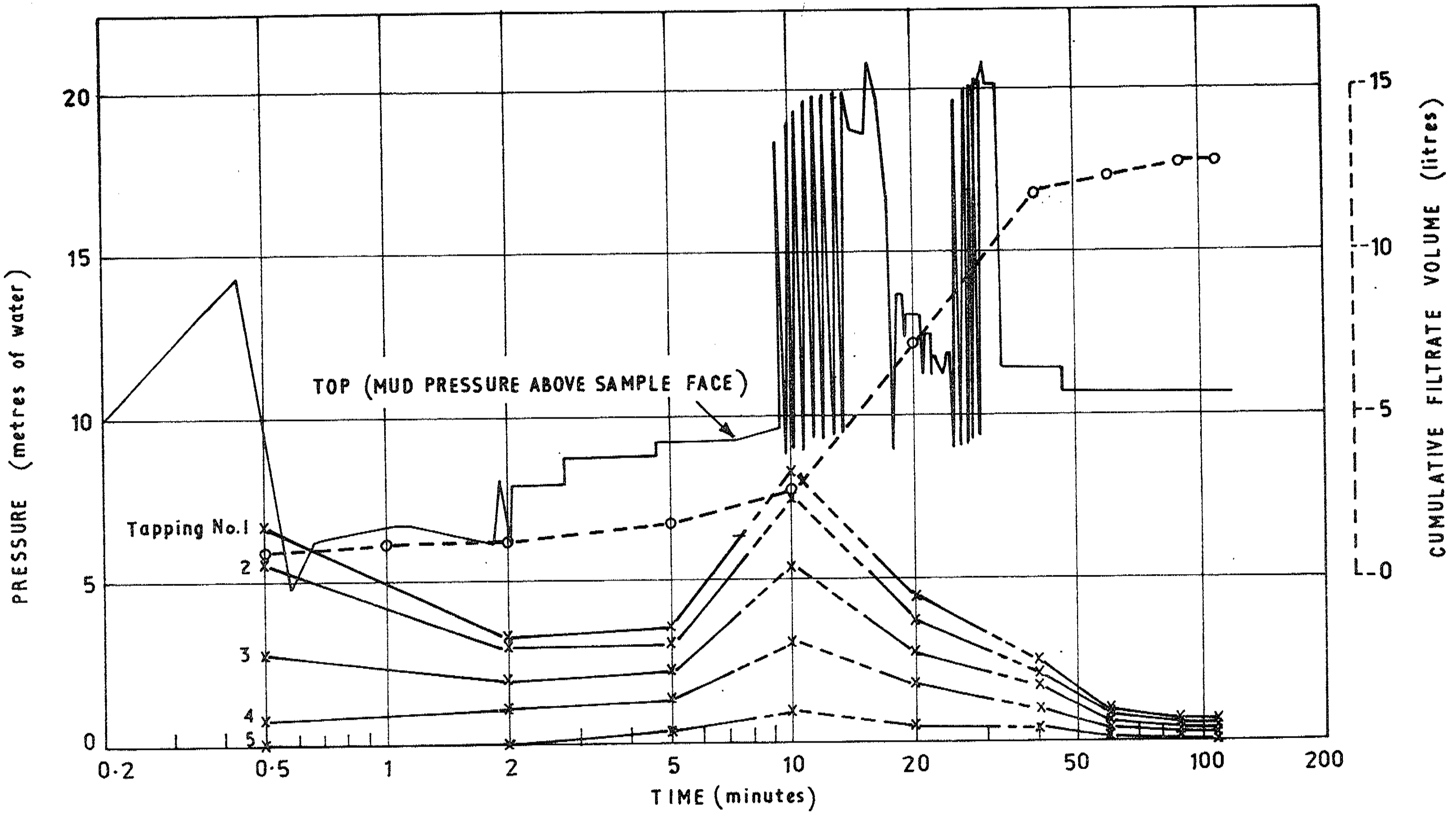


FIGURE 11·9 TEST 011 MATERIAL 3.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

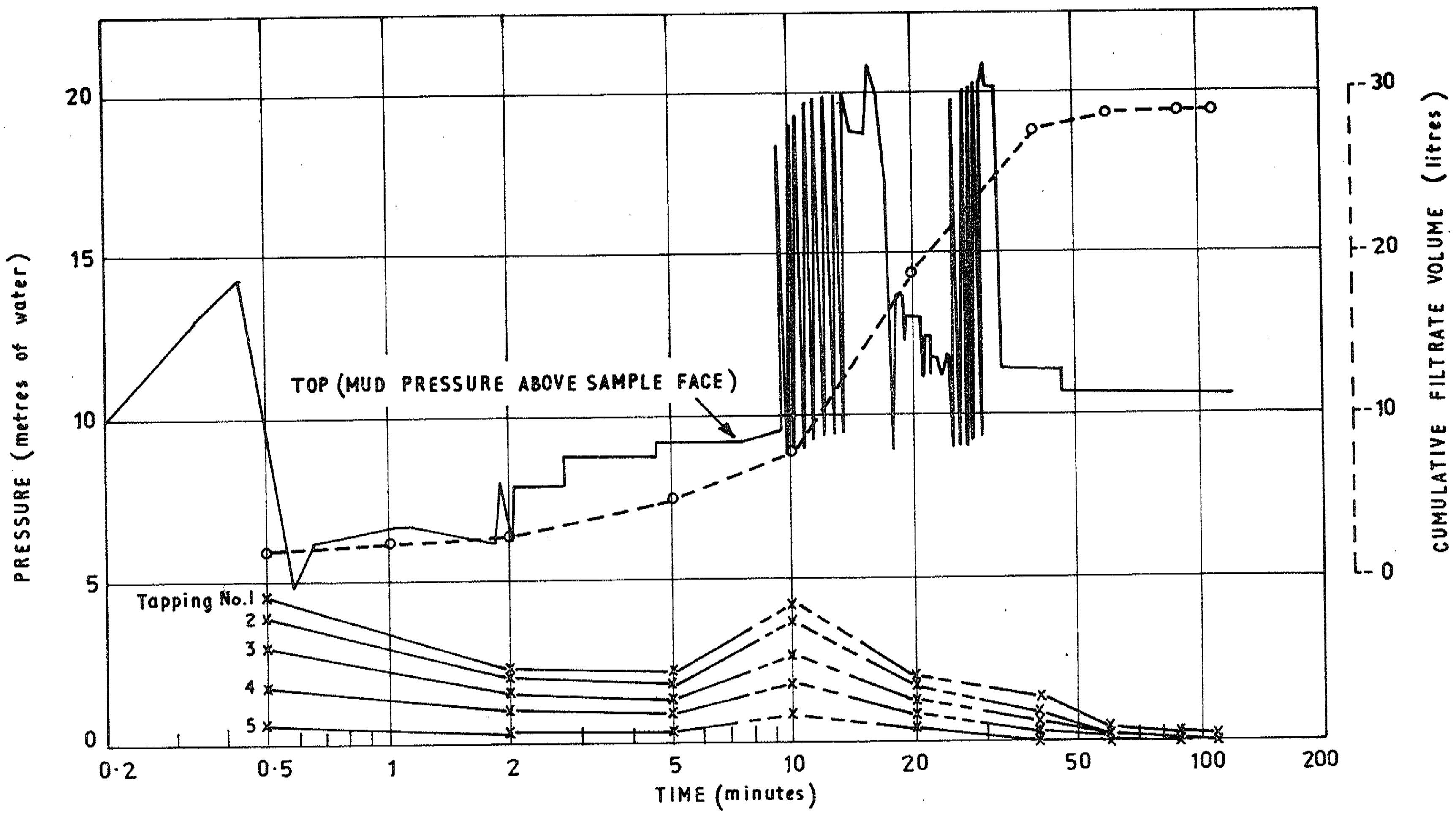


FIGURE 11·10 TEST 011 MATERIAL 4.

BEHAVIOUR DURING TIME OF EXPOSURE TO DRILLING MUD.

Table 11.1 Test 011

Permeability testing of material samples.

Values of pressure (metres of water) as recorded at various positions along the sample for a measured flow of water through the sample.

Material	Flow Rate litres/min.	Velocity mm/min.	Tapping No.					
			Top	1	2	3	4	5
			Position along sample from datum (mm)					
			0	64	114	216	318	420
Material Tests before Exposure to Drilling Mud								
1	2.88	448	13.45	11.85	10.15	7.12	3.91	1.07
	2.02	314	9.25	8.13	7.00	4.92	2.71	.76
	0.82	128	3.82	3.49	2.99	2.08	1.20	.32
2	6.56	1021	14.06	12.04	10.27	7.25	3.72	.82
	4.65	723	9.17	7.88	6.74	4.73	2.33	.51
	2.21	343	3.82	3.41	2.90	2.08	1.07	.26
3	30.15	4687	13.91	12.48	11.03	8.13	5.48	2.71
	22.56	3507	8.94	7.88	7.00	5.11	3.34	1.58
	14.18	2205	4.20	3.81	3.34	2.40	1.54	.63
4	47.37	7364	11.62	10.90	9.96	8.32	6.68	4.73
	37.66	5854	7.80	7.31	6.68	5.61	4.48	3.09
	26.55	4127	3.97	3.78	3.47	2.90	2.27	1.52
Material Tests after Exposure to Drilling Mud Initial Flushing - Water only								
1	2.21	343	13.83	11.09	9.77	6.56	3.59	0.95
	1.46	227	9.40	7.44	6.56	4.41	2.40	0.63
	0.58	90.2	3.67	2.90	2.52	1.70	0.95	0.26
2	5.26	818	14.06	12.16	10.15	7.00	3.41	0.76
	3.64	566	9.33	8.13	6.87	4.73	2.33	0.57
	1.84	286	4.28	3.78	3.22	2.21	1.07	0.26
3	18.75	2915	14.68	7.63	6.62	4.54	2.84	1.20
	13.39	2082	9.33	4.60	3.97	2.71	1.64	0.63
	7.11	1105	3.59	1.77	1.52	1.01	0.57	0.19
4	36.14	5619	11.69	9.52	8.26	6.37	4.73	2.96
	28.75	4470	7.80	6.24	5.42	4.16	3.09	1.96
	20.48	3183	3.97	3.34	2.90	2.21	1.58	1.01

Table 11.1 Test 011 (cont'd.)

Material	Flow Rate litres/ min.	Velocity mm/ min.	Tapping No.					
			Top	1	2	3	4	5
			Position along sample from datum (mm)					
			0	64	114	216	318	420
Material Tests after Exposure to Drilling Mud Final Flushing - P.B.D. Treatment and Further Water Flushing								
1	2.29	356	14.37	11.66	10.08	6.49	3.47	.89
	1.59	247	10.01	8.13	7.06	4.54	2.40	.63
	.56	87.3	3.60	3.09	2.65	1.70	.89	.26
2	4.80	746	13.68	11.97	9.89	6.62	3.22	.70
	3.15	490	8.48	7.44	6.18	4.16	1.96	.44
	1.63	253	3.90	3.59	2.96	2.02	.95	.19
3	16.00	2487	14.06	6.56	5.74	3.91	2.40	.95
	12.35	1919	9.48	3.97	3.47	2.40	1.45	.51
	7.28	1132	4.59	1.83	1.64	1.07	.70	.19
4	38.05	5916	11.85	10.02	8.76	6.81	5.11	3.28
	30.00	4664	8.03	6.74	5.86	4.54	3.34	2.15
	20.98	3261	4.13	3.53	3.09	2.33	1.70	1.07

Table 11.2 Test 011

Sample behaviour during time of exposure to drilling mud.

Pressure (metres of water)

Material	Time (minutes)	Filtrate Volume (litres)	Tapping No.					
			Top	1	2	3	4	5
			Position along sample from datum (mm)					
			0	64	114	216	318	420
1	½	.185	10.00	1.96	1.20	.70	.44	.32
	1	.24	6.60					
	2	.26	7.00	1.20	.32	.19	.19	.07
	5	.33	9.10	1.70	.44	.19	.19	.19
	10	.43	9.0 to 19.0	3.47	1.45	.19	.19	.19
	20	.645	13.0	5.23	3.59	.82	.19	.19
	40	.815	11.40	4.10	2.59	1.20	.32	.32
	60	.88	10.70	2.46	2.08	1.07	.19	.19
	90	.94	10.70	2.40	1.96	1.07	.32	.07
	110	.985	10.70	2.40	1.96	1.20	.44	.07
2	½	.305	10.0	3.72	1.58	.32	.19	.07
	1	.32	6.6					
	2	.355	7.0	1.58	.82	.19	.07	.07
	5	.45	9.1	1.96	1.07	.19	.07	.07
	10	.575	9 to 19	4.10	3.34	.70	.07	.07
	20	.86	13.0	2.46	1.96	1.26	.32	.07
	40	1.10	11.4	1.96	1.45	.95	.44	.07
	60	1.18	10.7	1.33	1.07	.70	.19	.07
	90	1.26	10.7	1.07	.82	.51	.26	.07
	110	1.31	10.7	.95	.82	.51	.26	.07
3	½	1.0	10.0	6.74	5.61	2.84	.82	.07
	1	1.2	6.6					
	2	1.3	7.0	3.34	2.96	1.96	1.07	.07
	5	1.8	9.1	3.59	3.09	2.21	1.33	.44
	10	2.85	9to 19	8.38	7.50	5.36	3.09	.95
	20	7.25	13.0	4.35	3.72	2.71	1.70	.44
	40	11.8	11.4	2.46	2.08	1.58	.95	.32
	60	12.4	10.7	.82	.70	.57	.32	.19
	90	12.7	10.7	.57	.44	.32	.19	.07
	110	12.8	10.7	.51	.44	.32	.19	.07

Table 11.2 Test 011 (cont'd.)

Material	Time (minutes)	Filtrate Volume (litres)	Pressure (metres of water)					
			Tapping No.					
			Top	1	2	3	4	5
			Position along sample from datum (mm)					
			0	64	114	216	318	420
4	$\frac{1}{2}$	2.0	10.0	4.60	3.97	3.09	1.83	.70
	1	2.5	6.6					
	2	3.0	7.0	2.33	2.08	1.58	1.07	.44
	5	5.0	9.1	2.21	1.83	1.33	.95	.32
	10	8.1	9 to 19	4.22	3.72	2.71	1.83	.95
	20	18.9	13.0	1.96	1.70	1.33	.82	.32
	40	27.6	11.4	1.33	.82	.70	.19	.07
	60	28.5	10.7	.44	.32	.32	.19	.19
	90	28.7	10.7	.13	.07	.07	.07	0
	110	28.8	10.7	.13	.07	.07	.07	0