Hydraulics Research
Wallingford

CONSOLIDATION AND EROSION OF ESTUARINE MUD AND SAND MIXTURES

An Experimental Study

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Report No SR 149
February 1988

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CONTRACT

This report describes work funded by the Department of the Environment under Research Contract PECD 7/6/57 for which the DoE nominated officer was Dr R P Thorogood. It is published on behalf of the Department of the Environment, but any opinions expressed in the report are not necessarily those of the funding department. The work was carried out by Mr R J Jones, Ms M C Ockenden and Mr A P Diserens and the report compiled by Ms M C Ockenden under the direction of Dr E A Delo in Mr T N Burt's section of the Tidal Engineering Department of Hydraulics Research, Wallingford under the management of Mr M F C Thorn.

ABSTRACT

The prediction of sediment transport has many important applications in the estuarine environment, such as the control of siltation and dredging and the assessment of pollution transfer. Understanding the physical mechanisms of consolidation and erosion leads to a better evaluation of sediment movement. Many estuaries contain a significant proportion of sand either in the bed or moving in the water column, which may affect the consolidation and erosional properties of the mud. This report describes recent laboratory studies carried out by Hydraulics Research (HR) to investigate the consolidation and erosional properties of mud/sand mixture beds.

A series of consolidation tests was performed in settling columns to investigate the deposition and consolidation of a premixed mud/sand suspension. The percentages of sand used, as percentages of the total dry weight of material, were 0%, 50% and 66%, with the actual concentrations of mud and sand chosen to give two different bed thicknesses for each percentage. The tests revealed that the sand settled out of suspension first to form a layer at the bottom of the bed.

A second series of consolidation tests was carried out involving the continuous deposition of mud alone from a suspension pumped into the column at a constant rate for each test. A suspension of mud was used at two different concentrations; the input rate and duration of input varied between tests. The resulting final density profiles suggested that the profile of the fully consolidated mud bed is independent of deposition rate or duration of input, and is determined by the effective stress with voids ratio relationship.

A third series of consolidation tests was run, to look at the effect of varying amounts of sand in the input suspension of a continuous deposition test. Five different percentages of sand were used, from 0% to approximately 60% of the total dry weight of material. The input rate and duration of input were chosen to give two different bed thicknesses for each ratio. The increasing proportion of sand in the suspension was reflected by increasing density, at a fixed depth. During the 7 days consolidation the sand settled out of the top part of the bed to leave a sand free layer. The density in this sand free layer at a fixed depth increased with increasing percentage of sand.

A new erosion test procedure was developed to simulate the slowly increasing and decreasing bed shear stresses encountered in natural conditions. Four erosion tests were undertaken in the HR mud carousel, with the rate of increase of shear stress systematically reduced between tests. The erosion constant for each run of each test was calculated and was found to decrease as the rate of increase of shear stress was reduced.

Five erosion tests were conducted in the carousel on mud/sand beds. A special hopper was used to sprinkle the sand into the carousel some time after a mud bed had settled. Five different percentages of sand were used in the top 5mm of the bed, from 0% to approximately 66% of the total dry weight of material. The same stepped bed shear stress pattern was applied in each test. The concentration of suspended mud was seen to increase for a particular constant bed shear stress as the amount of sand was reduced.

FIGURES

Consolidation and erosion of estuarine mud and sand mixtures

An experimental study SR 149

ERRATA 12.10.89

p25, last paragraph, line 5

"The graphs for Tests 2 to 4 (Figs 29-31) all indicate a value of the erosion constant m_e of around 0.0002kg/N/s. However, Test 5 (Fig 32) which had no sand shows a value of m_e in the range 0.0004 to 0.0006kg/N/s."

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p29, 3rd paragraph, line 11

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Fig 29	Vertical scale (previously 0.0-2.0) should cover range 0.0 - 4.6			
	Labels on lines:	m = 0.0002	should read	m = 0.0005
Fig 30	Vertical scale (previously 0.0-2.0) should cover range 0.0 - 4.6			
	Labels on lines:	m = 0.0002	should read	m = 0.0005
	Labels on lines:	m = 0.0003	should read	m = 0.0007
Fig 31	Vertical scale (previously 0.0-2.0) should cover range 0.0 - 4.6			
	Labels on lines:	m = 0.0002	should read	m = 0.0005
	Labels on lines:	m = 0.0001	should read	m = 0.0002
Fig 32	Vertical scale (previously 0.0-2.0) should cover range 0.0 - 4.6			
	Labels on lines:	m = 0.0004	should read	m = 0.0009
	Labels on lines:	m = 0.0006	should read	m = 0.0014

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1 INTRODUCTION

The prediction of sediment transport has many important applications in the estuarine environment, such as the control of siltation and dredging and the assessment of pollution transfer. Understanding the physical mechanisms of consolidation and erosion leads to a better evaluation of sediment movement. Many estuaries contain a significant proportion of sand either in the bed or moving in the water column, which may affect the consolidation and erosional properties of the mud. During a period of slack water, the flux per unit area of both mud and sand to the bed of such an estuary can be estimated. From this, it would be very useful to be able to assess both the short term and longer term re-erosion characteristics of this type of deposit. For this purpose, it is necessary to investigate how the presence of the sand affects the surface density of the bed, the critical shear stress for erosion of the bed surface and the density-depth profile of the bed.

In the past, work has been done on sand/mud beds by Bassi (1985) but this study covered predominantly sand beds, as frequently found in rivers. The percentages of silt used in this work did not even change the median particle size of the sediment and cannot therefore be directly applied to estuaries which are predominantly cohesive sediment with some sand. Laboratory studies have been carried out at Hydraulics Research (HR) to investigate these consolidation and erosional properties of mud/sand mixture beds.

The programme of work consisted of:

i) Settling and consolidation tests on mud and mud/sand mixtures, both from a premixed suspension and by continuous deposition, to examine the density structure of the bed formed.

ii) Erosion tests on mud beds to investigate the influence of the rate of increase of applied bed shear stress on the erosion characteristics of the mud.

iii) Erosion tests on mud/sand mixture beds to examine the effect of the sand fraction on the erosion of the mud.

This report describes these recent studies at HR. The consolidation tests are described, with results, in Section 2. Section 3 reports on the erosion tests with varying rates of increase of applied bed shear stress and Section 4 describes the erosion tests on mud/sand mixture beds. The conclusions drawn from all the tests are given in Section 5, along with recommendations for further work to be done in this field.

2 CONSOLIDATION TESTS

2.1 Description of apparatus

The tests were carried out in a 2 metre settling column of 92mm internal diameter, constructed of perspex sections (see Fig 1). A sampling port at a height of 0.5m above the base of the column was used in the single shot tests to enable small volumes of the suspension to be withdrawn for concentration and salinity analysis. A second port hole at the same height was used in the continuous deposition tests to inject a steady stream of a premixed suspension into the column, which was initially full of saline water. An outlet at 1.5m above the base of the column was used to extract the excess clear water above the settling bed. The suspension to be injected was kept constantly mixed by a recirculating pump. It was then extracted from the bottom of the mixing tank by a variable speed peristaltic pump and injected into the column. A constant rate of input over a set period of time was chosen for each test.

Density profiles were obtained for each bed in the settling column by measuring the transmission of emissions from a ^{133}Ba source over 30 seconds at 2mm or 5mm vertical intervals throughout the depth of the bed. The interval used was dependent on the thickness of the bed and was chosen to give approximately 10 readings for each bed.

2.2 Experimental accuracy

The time quoted for each density profile was the average time for the density readings in that profile, as it took around 10 minutes for each complete profile. It was assumed that there was no significant change in density over the time period taken to read the profile. There was a standard deviation for the density readings found in previous investigation by Hydraulics Research of ±1%. The vertical height (at 2mm or 5mm intervals) was read with an accuracy of ±0.25mm. The density probe was calibrated regularly by measuring the count rate in saline solutions of known density. This indicated a linear relationship over the density range applicable in the tests of the form

$$\rho_b = K_1 r + K_2 \qquad (1)$$

where

ρ_b = bulk density (kg/m^3)

r = count rate per minute

K_1, K_2 = constants

Because the total quantity of sediment put into the column during each test was known, integration of the density profiles should indicate (i) the distribution of mass through the column and (ii) the total mass in the column.

2.3 Test Procedure

The mud used throughout the experimental investigation was Hong Kong mud. This was sieved through a 200μm sieve to remove shells, sand and large organic particles. A stock suspension was made up of $30kg/m^3$ mud at $30kg/m^3$ NaCl. This suspension was diluted as necessary for each test with a saline solution of $30kg/m^3$ NaCl. The sand used was King's Lynn sand with a median particle size d_{50} = 230μm, and only 2% of the particles less than 100μm.

For the Series A tests (single shot) a suspension of mud or mud/sand was diluted to the required concentration and thoroughly mixed before pouring into the settling column to the required depth.

For the Series B and C tests (continuous deposition) the column was first filled with a saline solution of $30kg/m^3$ NaCl to the height of the overflow outlet. A suspension of mud (Series B) or mud/sand (Series C) was made up to the required concentration and kept thoroughly mixed in the conical-bottom mixing tank by the recirculating pump. At the start of the test the peristaltic pump was switched on to allow the suspension into the column. The speed of the pump was chosen according to the thickness of bed required and was left running for either 2 or 4 hours.

During the first day of each test a density profile was obtained and the bed thickness was recorded every 30 minutes. Subsequent density profiles and bed thicknesses were recorded at approximately 24 hour intervals until the bed had consolidated for 7 days.

In the Series B and C tests (continuous deposition), samples of the suspension being injected by the peristaltic pump were taken at regular intervals during the 2 or 4 hour input phase. These were analysed for mud and sand concentrations, to check on the mixing of the suspension.

2.4 Description of tests

The Series A tests (single shot) were conducted to illustrate that a mud/sand suspension would settle and consolidate to form a bed with significant particle size segregation as a result of the sand settling out more quickly at the bottom of the bed. The percentages of sand used in the tests were 0%, 50% and 66% of the total dry weight of material. For each percentage, suspensions were prepared to give a bed of approximately 20mm and a bed of approximately 50mm, settled from a column filled to a height of 2m. The required bed thickness and suspension compositions are summarised in Table 1.

The Series B tests (continuous deposition, mud only) were done to evaluate the apparatus and to investigate the effect of deposition rate on the consolidation of a mud bed. In particular these tests were conducted to examine the assumption that there is a unique relationship between effective stress and voids ratio (see Delo, 1987). The concentration of the continuous input suspension was either 6.0kg/m^3 or 3.0kg/m^3. The duration of the input was either 2 hours or 4 hours. For each combination of duration of input and concentration, the input rate, controlled by the peristaltic pump, was chosen so that beds of approximately 20mm or 50mm were produced. These parameters are tabulated for the Series B tests in Table 2.

The Series C tests (mud/sand continuous deposition) were conducted to investigate the effect of varying amounts of sand on the consolidation and density profile. The mud concentration of the continuous input suspension was approximately 6kg/m^3 mud in each test. The duration of the input was 2 hours where a bed of approximately 20mm was required and 4 hours where a bed of 50mm was required. Five different percentages of sand were used at each bed thickness, varying from 0% to approximately 60% of the total dry weight of material. These values are tabulated for the Series C tests in Table 3.

2.5 Results

2.5.1 Single shot - Series A

The results of the single shot tests are plotted as final density profiles after 7 days in Figure 2 (approximately 20mm beds) and Figure 3 (approximately 50mm beds). Figure 2 shows that below a depth of 6mm the presence of the sand can be clearly seen by the rapid increase in density with depth. For the case with 66% sand the density at a height 3mm above the bottom of the bed is approximately 1100kg/m^3. This compares with 650kg/m^3 at the same height for the case with 50% sand and only 350kg/m^3 for the bed of mud with no sand at all. In the top part of the bed a trend of increased density at a fixed depth can be seen with the increased percentage of sand. At a depth of 5mm from the surface, the density for the case with 66% sand is 280kg/m^3, compared with 170kg/m^3 for 50% sand and 140kg/m^3 for 0% sand. A similar pattern is observed at 3mm from the surface with densities of 230kg/m^3, 140kg/m^3 and 100kg/m^3 for 66%, 50%, and 0% sand respectively.

The final density profiles for the 50mm beds (Fig 3) also show this pattern. The presence of the sand can be seen in the bottom 15mm of the beds with a rapid increase in density with depth. At a height of 5mm above the bottom of the bed the density for the case with 66% sand is approximately 1200kg/m^3, compared with 1100kg/m^3 for 50% sand and 350kg/m^3 for 0% sand. Increasing density at a fixed depth below the surface for increasing percentages of sand can also be seen in Figure 3. At a depth of 10mm below the surface, the density for the case with 66% sand is 290kg/m^3, compared with 250kg/m^3 for 50% sand and 170kg/m^3 for 0% sand. From the continuous deposition tests (see 2.5.3) a similar trend was found in the top part of the bed, when it was shown in addition that there was no sand in the top part of the bed. It is very likely, therefore, that there is no sand in the top part of the beds in the single shot tests. The results for the single shot tests support the idea proposed later (see 2.5.3) that the passage of the sand has affected the density in the upper part of the bed.

Size gradings of the particles in the top millimetre and the bottom millimetre of the bed for Test A4 (50mm, no sand) and Test A6 (50mm, 66% sand) are given in Figure 4, showing the percentage, by dry weight, of particles below a given diameter. In both tests the particles at the surface are fine silt, with approximately 90% of particles less than 10µm and 98% of particles less than 60µm. Both tests show clear particle size segregation between the top and bottom. Test A4 (with no extra sand) shows that the bottom is made up of silt particles with 70% less than 60µm and 90% less than 100µm, whereas Test A6 (66% sand) shows that the bottom is made up entirely of sand, with no particles less than 100µm and only 50% less than 300µm.

2.5.2 Continuous deposition - Series B

Figure 5 shows the variation of bed thickness against time for the 20mm beds in the Series B tests (mud only). Time is shown on a logarithmic scale as the greatest variation in bed thickness is at the start of the test. The differing deposition rate and duration of input of test B3 can be seen by the position of the peak in bed thickness. For tests B1 and B2 this peak occurs at approximately 160 minutes after the start of the test, when the maximum bed thickness is 32mm. For test B3, in which the deposition rate was approximately half that for B1 and B2 but the duration of input was 4 hours rather than 2 hours, the maximum bed thickness is 22mm after approximately 260 minutes. The lower maximum bed thickness of test B3 shows that the bed has already had time to consolidate a significant amount whilst it is still depositing. No difference can be noted between tests B1 and B2, which indicates that the concentration of the input suspension does not affect the consolidation of the bed provided that the deposition rate is the same. After 10,000 minutes (7 days) all three beds have reduced in bed thickness to 16-17mm which suggests that the time and rate of deposition does not affect the final bed thickness.

The final density profiles after 7 days for the Series B tests are shown in Figure 6 (20mm beds) and Figure 7 (50mm beds). In each figure the profiles are quite similar, with little difference in the final profiles which might be due to the differing deposition rates. For the thinner beds (Fig 6) the densities are all in the range 60-100kg/m^3 at a point 2mm below the surface, rising to 200-280kg/m^3 at a point 15mm below the surface.

These profiles are similar to the profiles for the top half of the thicker beds (Fig 7) where the densities are also in the range 60-100kg/m^3 at a point 2mm below the surface and 200-230kg/m^3 at a point 15mm below the surface. The densities then increase to 280-350kg/m^3 at a depth of 30mm. Test B4 shows slightly lower densities at a fixed depth below the surface than Tests B5 and B6, but below a depth of approximately 12mm from the surface the density has increased to 220kg/m^3, similar to Tests B5 and B6. These results would seem to support the theory of a unique relationship between effective stress and voids ratio which determines the profile when consolidation is complete.

Since effective stress is a function of cumulative mass from the surface and voids ratio is a function of density, the relationship may also be expressed between the depth from the surface and density (see, Delo 1987). Figure 8 shows the final density profile for each 20mm bed plotted as density against depth from the surface. Also shown are the best fit lines from which the effective stress against voids ratio relationships were derived for each test (Fig 8). The effective stress varied from 0N/m^2 at the surface of the bed (voids ratio >65, dry density <40kg/m^3) to 15N/m^2 at a voids ratio of 8 (dry density $\approx$ 300kg/m^3). Similarly, Figure 9 shows density against depth from the surface for each 50mm bed, with best fit lines for each test. The corresponding effective stress against voids ratio relationships are also shown in Figure 9. Once again the effective stress varied from $0N/m^2$ at the surface of the bed to approximately $15N/m^2$ at a voids ratio of 8-10.

2.5.3 Continuous deposition - Series C

The results of the Series C tests (mud/sand) are shown as final density profiles in Figure 10 (20mm nominal beds) and Figure 11 (50mm nominal beds). It can be seen in both figures that only with more than 50% sand does the sand significantly affect the depth of the fully consolidated bed, where it adds approximately 5mm to the thinner beds (Fig 10) and 8-10mm to the thicker beds (Fig 11). A sand content of 50% by dry weight represents less than 10% by volume. The increasing proportion of sand in the input suspension is shown by the increased density at a fixed depth, particularly in the lower part of the bed. In the thinner beds (Fig 10) the densities at a point 4mm from the bottom of the bed were $280kg/m^3$, $620kg/m^3$, $630kg/m^3$, $750kg/m^3$ and $900kg/m^3$ for sand (by total dry weight) of 0%, 19%, 41%, 50% and 57% respectively. In the thicker beds (Fig 11) the densities at a point 10mm from the bottom of the bed were $290kg/m^3$, $510kg/m^3$, $670kg/m^3$, $750kg/m^3$ and $890kg/m^3$ for sand contents of 0%, 18%, 32%, 37% and 53% respectively.

The stepped profiles indicate that after 7 days consolidation the sand has settled down through the bed leaving only mud in the top part of the bed. The profiles show a more sudden increase in density with depth, usually just after the density reaches $200kg/m^3$. The depth of the bed with a density less than $200kg/m^3$ is tabulated for each test in Table 3. As a general trend the depth of this lower density part of the bed decreases as the proportion of sand increases. Test C9 fits in to the trend shown by the lower part of each bed but is unusually dense in the top few millimetres.

The development of the sand-free layer can be seen in Figure 12 which shows density profiles at successive times for Test C2 (20mm bed, 19% sand). The first profile shown was taken after 2 hours, at the end of the input phase. Although the bed had not yet reached its maximum thickness, the profile is a smooth curve with no sudden increases in density for a small increase in depth, which indicates that the sand is still present throughout the depth. At successive times the density at the bottom of the bed increases, whilst towards the top of the bed the density decreases as the sand settles through it. This results in the final stepped profile (as in Fig 10).

The formation of the bed can be followed by looking at the dry density of the material at 3mm below the surface of the bed with time, as shown in Figure 13 (20mm beds) and Figure 14 (50mm beds). Time is shown on a logarithmic scale as there is a greater change in bed thickness in the first few hours of each test. In each figure there is a period of rapidly decreasing near-surface density which reaches a minimum soon after the start of the test and then slowly rises again, levelling off towards the end of the test. The rapid decrease in density corresponds to the formation phase of the bed. Just after the start of the test the bed is very thin and contains a high proportion of sand which has already settled out whilst the mud is still settling from the suspension. As the bed builds up, the mud settling together with the sand lowers the density, until a minimum is reached about one hour after the end of the input phase (ie at 3 hours in Figure 13 and at 5 hours in Figure 14). This coincides with the time of maximum bed thickness, when all or most of the material has deposited. Thereafter the material begins to consolidate faster than the deposition of any remaining material. Following this minimum value of near-surface density the bed consolidates, indicated by the rise in density which levels off towards the end of the test.

The effect of the sand can be seen generally to raise the surface density of the final bed. In Figure 13 (20mm beds) the presence of 19% sand has no noticeable effect, leaving the near-surface density at approximately $100kg/m^3$, as for no sand. For 50% sand the density is around $140kg/m^3$ and both 41% and 57% sand give around $180kg/m^3$. This suggests that small percentages of sand have little effect on the surface density whilst larger percentages increase the density up to a maximum value. In Figure 14 (50mm beds) the densities are $100\text{-}110kg/m^3$ for 0%, 18% and 32% sand and approximately $180kg/m^3$ for 37% and 53% sand. This again supports the idea that the larger percentages of sand have increased the final surface density but only up to a maximum of around $180kg/m^3$.

This presents an interesting question because, as already demonstrated by the final density profiles, the top part of each final bed contains no sand. Size gradings at several points in the bed are shown for Test C6 (0% sand) in Figure 15 and for Test C8 (32% sand) and Test C10 (53% sand) in Figure 16. From Figures 15 and 16 together, it can be noted that the size gradings at 18mm below the surface in tests C8 and C10 both show slightly higher percentages of the more coarse silt particles than for the bottom of the bed in test C6 (no sand). From Figure 16 it can also be seen that at both the surface and 18mm below the surface the size gradings are very similar for the tests with 32% sand and 53% sand and that there are no particles less than 100μm, which indicates that there is no sand in this part of the bed. However, from Figure 14, the near-surface densities for 32% sand and 53% sand are 110kg/m^3 and 180kg/m^3 respectively, compared with 100-110kg/m^3 for no sand. From Figure 11 the densities at 18mm below the surface are 320kg/m^3 for 32% sand and 430kg/m^3 for 53% sand, as compared with 200kg/m^3 for no sand.

The information from the size gradings and the density profiles together indicates that the passage of an increased percentage of sand through the top part of the bed has made little or no change to the particle content in this part of the bed but has caused the density to increase. This means that the mud aggregates must be more tightly compacted. One possible cause of this is that the sand has passed through the mud taking the fine silt particles with it, thereby leaving the more coarse silt particles in the upper region, giving a higher density profile. An alternative explanation is that the downward passage of the sand particles has left drainage paths in the overlying mud through which the water has been expelled more quickly from the mud bed, causing more consolidation. A greater percentage of sand would leave more such drainage paths and hence cause greater consolidation.

The maximum surface density of 180-200kg/m^3 for both 37% and 53% sand (from Figure 14) suggests that a limit may have been reached in the consolidation, which is not exceeded by depositing material with a higher percentage of sand. An explanation of this could be that for higher percentages of sand the drainage paths caused by the sand are beginning to have two counter-balancing effects. It is possible that the higher percentages of sand leave more drainage paths and hence cause greater consolidation, but at the same time the drainage paths are leaving the mud matrix more open, therefore making the whole mud layer less dense, with the overall effect that the density is not increased beyond a certain limit.

Whilst the continuous deposition of mud and sand together has not resulted in homogeneous beds, it has nevertheless produced mud/sand mixture beds with the sand present in at least the bottom 50% of the bed. Figure 17 compares the bed produced by continuous deposition of a suspension with equal dry weights of mud and sand (Test C4) with that produced by a single shot test of the same suspension (Test A2). In the single shot test the sand only affects the bottom 30% of the bed. For the continuous deposition test the presence of the sand or the passage of the sand through the mud has affected at least 80% of the bed.

3 A NEW EROSION TEST PROCEDURE

3.1 Description

Erosion is the removal of sediment from the surface of the bed due to the stress of the moving water above the bed. To date, most laboratory studies of the erosion process have involved a constant rate of flow of the fluid for a fixed period of time, with this flow rate (and hence bed shear stress) being increased in discrete steps. In natural conditions the bed shear stress does not increase in steps but rather increases and decreases more slowly and smoothly. To simulate what happens in the field more closely a new erosion test procedure was investigated, without the discrete steps in bed shear stress.

The tests were run in the HR mud carousel (Fig 18), an annular flume with a detachable roof. The roof fits into the channel and floats on the fluid. Fluid motion in the carousel is induced and continued by the drag between the roof and the fluid surface as the roof rotates. The carousel is described in detail by Burt and Game (1985) and the operation and instrumentation by Delo (1987).

To prepare a mud bed in the carousel the mud is first mixed homogeneously in a mixing tank with a recirculating pump and then pumped into the carousel flume until the required depth of suspension is reached. Before each test, the mud is totally remixed into suspension in the flume and allowed to settle and consolidate for a fixed period of time. The depth of fluid above the bed is adjusted to be close to 100mm which corresponds to the depth of flow for which the bed shear stress measurements were made.

The average bed shear stress across the width of the flume measured by laser anemometry (see Delo, 1987) is given in Figure 19. The average shear stress on the wetted perimeter as given by the energy input measured through the strain gauge divided by the wetted surface area is also shown in Figure 19. These two curves show reasonable agreement and indicate a steady increase in bed shear stress with increasing speed of rotation of the roof. For the purpose of estimating the bed shear stress during an erosion test the curve representing the average shear stress as calculated from the energy input was used. However, it must be appreciated that in an erosion test the fluid in the carousel may have a high concentration of suspended solids and therefore may behave slightly differently from the clear water in which the calibrations were made.

Each erosion test comprised 3 or 4 discrete runs each lasting 60 - 200 minutes. A run commences when the concentration of suspended solids is constant in the previous run. The speed of rotation of the roof (and hence bed shear stress) is then increased slowly from the previous equilibrium value to a new value. The rate of increase of shear stress is fixed at the start of the test and varies from $0.05N/m^2/hr$ to $0.5N/m^2/hr$. This new value of the shear stress is then held until the concentration of suspended solids (as measured continuously by the densiometer) becomes constant once again. This signals the equilibrium condition and the end of the run. The thickness of the bed is measured from beneath the flume by an ultrasonic transducer. The readings from the transducer reflect the pattern shown by the concentration, with a gradual change during the period of increasing shear stress which then tails off once the new shear stress has been reached and finally remains nearly constant.

3.2 Test Programme

The carousel was filled to a depth of 0.120m with a suspension of $28.5kg/m^3$ suspended solids (Hong Kong mud) and $35.7kg/m^3$ salt. The consolidation period for each of the tests was 3.7 days. The rate of increase of bed shear stress was approximately $0.4N/m^2/hr$ for Test 1. This was decreased to $0.2N/m^2/hr$ in Test 2, $0.1N/m^2/hr$ in Test 3 and $0.05N/m^2/hr$ in Test 4. These values are summarised in Table 4 with the final roof rotation speed for each run in the four tests. In Tests 2,3 and 4 the roof rotation speed was brought to 1.47rpm (approximately $0.08N/m^2$) before run 1. This was just below the critical shear stress for erosion and meant that erosion started soon after run 1 began.

3.3 Results

The roof speed, suspended solids concentration and depth of erosion during Test 1 are shown in Figure 20. The rate of increase of shear stress is relatively high ($0.4 N/m^2/hr$) and results in a large increase in concentration of suspended solids over a short period of time at the start of each run.

The roof speed, suspended solids concentration and depth of erosion during Tests 2, 3 and 4 are shown in Figures 21 to 23 respectively. The same final values of the shear stress for each run were applied in Test 2 as in Test 1, but during the third run there was a sudden increase in suspended solids concentration without a corresponding increase in shear stress. This was caused by lumps of mud being eroded from the surface. After this point it could be seen that the suspended solids were no longer evenly mixed throughout the depth and that the sediment-suspension interface was no longer so cleanly defined by the ultrasonic transducer. Test 2 was therefore stopped at this point. As the rate of increase of shear stress decreased from one test to the next, the rate of increase of suspended solids concentration also decreased.

Intuitively, one would expect erosion to start when the stress exerted by the flow exceeded the shear strength of the exposed bed and the erosion rate to depend on the excess shear. The most common representation of erosion is

$$\frac{dm}{dt} = m_e (\tau - \tau_e) \qquad (2)$$

where

$\frac{dm}{dt}$ = unit erosion rate ($kg/m^2/s$)

m_e = erosion constant ($kg/N/s$)

τ = applied shear stress (N/m^2)

τ_e = erosion shear strength (N/m^2)

Although there is no physical reason for assuming erosion rate to be directly proportional to the excess shear, Delo and Burt (1986) showed that this is a better variable for describing mud erosion than others.

An estimation of the erosion constant, m_e, can be made by calculating average values of the variables in equation 2 over the period during each run when the applied shear stress is increasing. The equation then becomes

$$\frac{\Delta M}{\Delta t} \simeq m_e \, \overline{(\tau - \tau_e)} \tag{3}$$

where

ΔM = change of mass per unit area during time Δt (kg/m^2)

Δt = time period of increasing shear stress (s)

$\overline{(\tau - \tau_e)}$ = average value of excess shear stress during time Δt (N/m^2)

The average values and resulting values of m_e are tabulated for each run of all four tests in Table 5. The change in mass is calculated from the change in concentration and the average depth of flow during the time period. The shear strength of the bed is calculated by assuming a linear relationship between the shear strength and the depth of erosion, defined by the values of these variables at the equilibrium position at the end of each run. The changing shear strength of the bed as the bed erodes is shown for Test 3 in Figure 24 together with the applied bed shear stress. The excess shear stress at any time is the difference between the two lines, and can be seen to be zero at the equilibrium positions when the bed has eroded down to a level where the bed shear strength is equal to the applied shear stress. The average value of the excess shear stress used in the calculations of the erosion constant is found by taking the average of the values at the start and end of the period of increasing shear strength.

The results show a considerable amount of variation within each test, which is mainly due to the natural variability of the mud and the difficulty of calculating the relationship between the depth of erosion and shear strength of the bed. In particular, run 1 in each test depends on the shear strength of the initial bed surface which is calculated on the basis of this relationship. However, considering all the tests together suggests that the rate of increase of shear stress may be related to the erosion constant; the erosion constant decreases from approximately 0.003kg/N/s when the rate of increase of shear stress is $0.4N/m^2/hr$ to approximately 0.0008kg/N/s when the rate of increase of shear stress is $0.05N/m^2/hr$.

3.4 Conclusion

The results presented suggest that the rate of increase of shear stress may be related to the erosion constant. It is recommended that further investigations be carried out on this aspect. For the purpose of this study it was therefore decided that the erosion test procedure described above was not as suitable for the mud/sand mixture tests as the method previously adopted for erosion tests, with discrete steps in the applied bed shear stress.

4 MUD/SAND EROSION TESTS

4.1 Bed Preparation

The deposition and consolidation tests described in Section 2 show that it is not possible to create a bed of mud and sand mixed throughout the depth by simply mixing the mud and sand into suspension and then allowing it to settle. The sand would settle out first as a layer at the bottom of the bed. Even the continuous deposition of mud and sand together eventually consolidates to leave a sand-free layer.

As the maximum depth of erosion of the bed during an erosion test is typically less than 0.005m, it was decided to first settle a bed of mud in the carousel and then add sand after a suitable interval or intervals so that the sand penetrated approximately to a depth of 0.005m from the bed surface and was present throughout the top 0.005m of the bed.

Preliminary tests were performed in settling columns using a mud suspension of the same concentration as in the carousel and adding sand at different times after the mud bed had settled. The total mass of sand added to each column was calculated to give approximately twice the mass of sand to mud (by dry weight) in the top 0.005m of the bed. The tests indicated that sand added less than 4 hours after the mud bed began to deposit tended to penetrate too deeply, leaving little or no sand in the top 0.005m of the mud bed. Also, sand added more than 14 hours after the start of settling of the mud bed stayed mostly on the surface of the mud bed. Sand added 7 hours after the mud began to deposit remained in the top 0.005m of the bed, as shown in Figure 25. This shows a density profile of the bed formed by adding sand after 7 hours and then allowing the bed to consolidate for 3 days. Also shown is a density profile of a similarly consolidated bed settled from the same initial suspension concentration but without the later addition of the sand. It can be seen that the presence of the sand in the top 0.005m greatly increases the density in that region.

A sand hopper was designed and made to introduce sand into the carousel, spreading a predetermined mass evenly over the whole surface area of the bed (Figure 26). The hopper consists of a trough of V-shaped cross-section with a horizontal slot along the bottom through which the sand falls. This trough is supported by four flanged wheels which run round the rim of the carousel once the roof has been removed. An adjustable plate allows the width of the slot to be altered to give a particular flow rate of sand. The hopper is pushed round the rim of the carousel by the drive arm and can therefore be driven at any desired speed by the microcomputer. By setting the flow rate of sand and the speed of the drive arm, a range of masses of sand can be distributed evenly over a complete number of revolutions of the arm.

4.2 Procedure

The carousel was filled to a depth of 0.113m with a suspension of 30.3kg/m^3 suspended solids (Hong Kong mud) and 35.7kg/m^3 salt. This suspension was thoroughly mixed in the flume and allowed to settle for a minimum of 6 hours before a certain mass of sand was sprinkled evenly on to the settling bed by the sand hopper, as described in Section 4.1. The total consolidation time for the bed was 3 days in each test.

Each erosion test on the mud/sand mixture beds comprised of 2-5 discrete runs each lasting 40-100 minutes. A run commenced when the concentration of suspended solids was constant in the previous run. The speed of rotation of the flume (and hence bed shear stress) was then increased quickly to a new value and held constant until the concentration of suspended solids became nearly constant once again, indicating no further erosion at that fixed bed shear stress. At this point in each run the shear strength of the exposed surface of the bed was equal to the applied shear stress.

4.3 Programme

For Test 1, the mud suspension in the carousel (see 4.2) was thoroughly mixed and allowed to settle for 6 hours. The sand hopper was then used to sprinkle 3.5kg of fine sand (King's Lynn, $d_{50} \simeq 230\mu m$) over the surface of the settling bed. After a further 5 hours the hopper was used to repeat the process with another 3.5kg of sand. The roof was then lowered on to the fluid surface and the bed was allowed to consolidate for a further 2½ days before testing. The percentage of sand in this test was nominally 66% of the total dry weight of material in the top 5mm of the bed.

For each subsequent test the bed left after the end of the previous test was remixed into suspension. Any sand from previous tests settled immediately to the bottom of the bed and therefore had no further effect on the following test. The volume of sand thus left at the bottom was negligible compared with the volume of the mud and therefore did not significantly alter the thickness of the bed. The percentages of sand by weight in the top 5mm of the bed for tests 2, 3, 4 and 5 were nominally 50%, 20%, 11% and 0% respectively. The consolidation period was 3 days in each test. The composition of the erosion test beds is summarised in Table 6.

Settling column tests were run concurrently with the erosion tests to check the sand content of each test bed. These tests showed that the actual sand content was within 10% of the nominal sand content and decreased in each successive test in the same way as the nominal percentages.

The same pattern of applied bed shear stress was applied to each test bed. The speeds of rotation of the roof successively applied were 2.17rpm, 2.52rpm 2.86rpm, 3.21rpm, 3.53rpm. The length of time that each of these speeds was held constant varied slightly from test to test, depending on the time taken for the equilibrium condition to be reached (no further erosion). In all tests apart from Test 1, mass erosion occurred during the 3rd or 4th run. This was characterised by a sudden increase in concentration with no corresponding increase in shear stress, and lumps of mud could be seen to have broken away from the surface. The tests were stopped after this point as erosion was irregular. The details of the runs in each test are summarised in Table 7.

4.4 Results

4.4.1 Erosion rate

The roof speed and suspended solids concentration during Test 1 (nominally 66% sand) are presented in Figure 27, showing very little increase in concentration for any of the applied bed shear stresses. The suspended solids concentrations during all the tests are shown in Figure 28. Noting that the same bed shear stress is applied in Run 1 of each test, and similarly Runs 2, 3, 4 and 5, it can be seen that the sand fraction is significantly reducing the amount of erosion. Test 5, with no added sand, shows much higher concentrations for each corresponding run than Test 3 (20% sand) which, in turn, shows higher concentrations than Test 1 (66% sand).

A useful analysis of the erosion constant can be made by assuming that the shear strength of the bed during any discharge run is proportional to the eroded mass (Miles, 1985). The constant of proportionality for a run is given by

$$\alpha = \frac{\tau_b - \tau_o}{c_e - c_o} \qquad (4)$$

where

τ_b is applied bed stress for the run
τ_o is shear strength of bed at start = equilibrium from previous run
c_e is equilibrium concentration at the end of run
c_o is initial concentration = equilibrium concentration at end of previous run

This does not assume that there is a linear relationship between strength of bed and overlying weight for the complete bed. This overall structure is fixed by the equilibrium conditions at the end of each run. It has merely been assumed that there is a linear variation from one equilibrium state to the next and α can vary for each run.

If we further assume that the erosion rate for the exposed mud surface area is given by equation (2) we obtain, using (4) and replacing m by cV/A

$$\frac{dc}{dt} = Am_e\alpha\ (c_e - c_o)/V \tag{5}$$

where V is the volume of fluid in the flume and A is the area of erosion. This can be integrated as

$$(c_e - c) = (c_e - c_o)\ \exp\ (-Am_e\alpha t/V) \tag{6}$$

This solution exhibits the expected behaviour of concentrations, tending to equilibrium values for large times. Based on the analytic form of this theoretical solution, the carousel erosion flume results for a test can be normalised and plotted using linear (αt) (m^2/s) and logarithmic $\left[(c_e - c_o)/(c_e - c)\right]$ axes to give a representative erosion constant for the test.

Tests 2 to 5 were analysed with the above method, but the increase in concentration was too small in Test 1 for this method of analysis. The normalised results of erosion rate are presented in Figures 29 to 32 for Tests 2 to 5 respectively. The graphs for Tests 2 to 4 (Figs 29-31) all indicate a value of the erosion constant m_e of around 0.0002kg/N/s. However, Test 5 (Fig 32) which had no sand shows a value of m_e in the range 0.0004 to 0.0006kg/N/s. This indicates that even a small percentage of sand (11%) affects the erosion rate and erosion constant.

4.4.2 Erosion shear strength and density

The shear strength of the exposed bed surface for each run of each test has been plotted against the depth of erosion in Figure 33. A linear relationship has been defined for Tests 2, 4 and 5. It can be seen that an increase in the percentage of sand reduces the depth of erosion for a given shear stress. By extrapolation back to the surface, the critical shear stress for erosion of tne initial surface also increases with increasing percentage of sand. The critical shear stress for movement of a sand only bed (sand particles of 230μm) is approximately $0.38 N/m^2$ (from Shield's diagram), which is still higher than the values indicated in Figure 33 of around $0.19 N/m^2$ for 50% sand and $0.11 N/m^2$ for 11% sand.

The shear strength of the exposed bed surface for the final run of Tests 1, 2, 4 and 5 has been plotted against the density at the maximum depth of erosion for each of these tests in Figure 34. At the equilibrium position the shear strength of the bed is equal to the applied bed shear stress which is related to the speed of rotation of the roof (see Fig 19). The densities have been taken from the density-depth profile of each test bed. Because the maximum depth of erosion was very small (approximately 0.001m in Tests 1, 2 and 4, 0.003m in Test 5) it was only possible to plot one point for each test, corresponding to the equilibrium position of the final run. Even for these points, the accuracy of the density profiles for points so close to the surface is estimated to be ±30%. Also shown in Figure 34 is a line of comparison from previous erosion tests on Hong Kong mud only beds (Hydraulics Research, 1987). The line illustrates for comparison the relationship found in this previous work which was

$$\tau_e = 0.0013\ \rho^{1.2}$$

The points for Tests 4 and 5 in Figure 34 lie close to this line, suggesting that the small percentage of sand in the bed in Test 4 has made little or no difference to the shear strength with density relationship.

The points for Tests 1 and 2 lie a considerable way from the line, suggesting that the much higher applied shear stress needed to erode a bed with a larger percentage of sand down to the same level as a mud only bed is not just due to the increased density of the bed resulting from the presence of the sand, but that there is a different shear strength with density relationship for mud/sand mixture beds.

It is not possible to determine the actual relationship with only one point from each test but it would appear that the same shear stress will erode down to a higher density if there is sand in the bed, although it should be remembered that this higher density will be much nearer the surface than for a mud only bed.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

1. Laboratory tests were undertaken to examine the effect of sand on the consolidation and erosion of a mud bed. The tests were carried out in the Hydraulics Research Laboratory using Hong Kong mud and King's Lynn sand (d_{50} = 230 μm).

2. A series of consolidation tests was performed in settling columns to investigate the deposition and consolidation of a premixed mud/sand suspension. The percentages of sand in terms of mud/sand dry weight studied were 0%, 50% and 66%. The actual concentrations of mud and sand were chosen to give two different bed thicknesses for each percentage. The tests revealed that the sand settled out of suspension first to form a layer at the bottom of the bed (Figs 2 and 3).

3. A second series of consolidation tests was carried out in settling columns to evaluate the apparatus and to determine an empirical relationship for a mud bed between voids ratio and effective stress. This involved the continuous deposition of material from a suspension pumped into the column at a constant rate for each test. A suspension of mud was used at two different concentrations; the input rate and duration of input varied between tests. The resulting final density profiles (Figs 6 and 7) suggested that the profile of the fully consolidated mud bed is independent of deposition rate or duration of input, and is determined by the effective stress with voids ratio relationship (Figs 8 and 9). The tests showed that the continuous deposition apparatus performed satisfactorily.

4. A third series of consolidation tests was run, to look at the effect of varying amounts of sand in the input suspension of a continuous deposition test. Five different percentages of sand were used in the suspension, from 0% to approximately 60% of the total dry weight of material. The input rate and duration of input were chosen to give two different bed thickness for each ratio.

The increasing proportion of sand in the suspension was reflected by increasing density at a fixed depth. During the 7 days consolidation the sand settled out of the top part of the bed to leave a sand free layer, the density of which depended on the percentage of sand which had passed through. Higher percentages of sand made no change to the size gradings in the sand free layer but increased the density there.

5. A new erosion test procedure was developed to simulate the slowly increasing and decreasing shear stresses encountered in natural conditions. Four erosion tests were undertaken in the mud carousel, with the rate of increase of shear stress systematically reduced between tests. The erosion constant for each run of each test was calculated which suggested that the erosion constant decreases as the rate of increase of shear stress decreases.

6. Five erosion tests were conducted in the carousel on mud/sand beds. A special hopper was used to sprinkle the sand in the carousel some time after a mud bed had settled. Five different percentages of sand in the top 5mm of the bed were used, from 0% to approximately 60%. The same stepped shear stress pattern was applied in each test with increased concentrations at each fixed shear stress as the sand fraction was reduced. The erosion constant, m_e, was evaluated for each run of Tests 2, 3, 4 and 5. The mean value of m_e for Tests 2, 3 and 4 (50%, 20%, 11% sand respectively) was around 0.0002kg/N/s, whereas for Test 5 (0% sand) m_e was in the range 0.0004 to 0.0006kg/N/s, which indicates that even

the presence of a small quantity of sand (11%) affects the erosion constant.

5.2 Recommendations

1. It is recommended that further laboratory studies be conducted on the possible relationship between the rate of increase of shear stress and the erosion constant m_e.

2. It is recommended that more work is undertaken to understand better the reason for the increased density in the sand free layer, after the downward passage of the sand.

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TABLES.

TABLE 1: Description of suspensions and resulting beds in Series A consolidation tests

TEST NO	DESIRED BED THICKNESS (mm)	CONCENTRATION OF MUD IN SUSPENSION (kg/m^3)	SAND CONTENT (% by dry weight of total)	ACTUAL BED THICKNESS AFTER 7 DAYS (mm)
A1	20	1.096	0	14.5
A2	20	1.194	50	13
A3	20	1.539	66	14
A4	50	3.664	0	32
A5	50	3.834	50	38
A6	50	3.854	66	40

TABLE 2: **Description of suspensions and resulting beds in Series B consolidation tests**

TEST NO	DESIRED BED THICKNESS (mm)	CONCENTRATION OF MUD IN INPUT SUSPENSION (kg/m^3)	INPUT RATE (m^3/hr)	DEPOSITION RATE ($kg/m^2/s$)	DURATION OF INPUT (hours)	ACTUAL BED THICKNESS AFTER 7 DAYS (mm)
B1	20	6.0	0.0015	$3.8\ 10^{-4}$	2	17
B2	20	3.0	0.0030	$3.8\ 10^{-4}$	2	17
B3	20	6.0	0.0009	$2.3\ 10^{-4}$	4	16
B4	50	6.0	0.0040	$1.0\ 10^{-3}$	2	34
B5	50	3.0	0.0080	$1.0\ 10^{-3}$	2	35
B6	50	6.0	0.0020	$5.0\ 10^{-4}$	4	37

TABLE 3: Description of suspensions and resulting beds in Series C consolidation tests

Input rate for tests C1 to C5 $0.0015m^3/hr$
Duration of input for tests C1 to C5 2 hours

Input rate for tests C6 to C10 $0.0020m^3/hr$
Duration of input for tests C6 to C10 4 hours

TEST NO	CONCENTRATION OF MUD IN INPUT SUSPENSION (kg/m^3)	CONCENTRATION OF SAND IN INPUT SUSPENSION (kg/m^3)	SAND CONTENT (by dry weight of total) (%)	ACTUAL BED THICKNESS AFTER 7 DAYS (mm)	DEPTH OF BED WITH A DENSITY LESS THAN $200kg/m^3$ (mm)
C1	5.9	0.0	0	17	11
C2	7.8	1.9	19	19.5	6.5
C3	8.9	6.2	41	18.5	4
C4	8.5	8.5	50	18	5
C5	11.9	15.7	57	24	4
C6	6.8	0.0	0	37	17
C7	9.1	1.9	18	40	10
C8	8.6	4.0	32	37	8
C9	10.6	6.1	37	38	3
C10	12.2	13.7	53	48	7

TABLE 4: Details of runs in erosion tests with slowly increasing shear stress

Depth of suspension for all tests	0.120	m
Concentration of suspension for all tests	28.5	kg/m^3
Salinity for all tests	35.7	kg/m^3
Consolidation period for all tests	3.7	days

TEST NO.	NUMBER OF RUNS	RATE OF INCREASE OF SHEAR STRESS	ROOF ROTATION SPEED (rpm)				TEMPERATURE
		$(N/m^2/hr)$	Run 1	Run 2	Run 3	Run 4	°C
1	4	0.4	2.17	2.86	3.21	3.53	11.4
2	3	0.2	2.17	2.86	3.21		11.6
3	4	0.1	2.17	2.53	2.87	3.21	10.8
4	3	0.05	2.17	2.53	2.87		11.4

TABLE 5: **Average values for estimation of erosion constant in tests with slowly increasing shear stress**

	CHANGE IN MASS	TIME PERIOD	$\frac{\Delta M}{\Delta t}$	AVERAGE APPLIED SHEAR STRESS	AVERAGE BED SHEAR STRENGTH	AVERAGE EXCESS SHEAR STRESS	EROSION CONSTANT
	ΔM (kg/m^2)	Δt (s)	($kg/m^2/s$)	$\bar{\tau}$ (N/m^2)	$\bar{\tau}_e$ (N/m^2)	$\overline{(\tau - t_e)}$ (N/m^2)	m_e (kg/N/s)
TEST 1	(Shear stress increasing at 0.4 $N/m^2/hr$)						
Run 1	0.061	2100	2.0 10^{-5}	0.155	0.149	0.006	0.005
Run 2	0.082	900	9.1 10^{-5}	0.262	0.233	0.029	0.003
Run 3	0.007	600	1.2 10^{-5}	0.338	0.310	0.028	0.0004
Run 4	0.027	900	3.0 10^{-5}	0.405	0.382	0.023	0.001
TEST 2	(Shear stress increasing at 0.2 $N/m^2/hr$)						
Run 1	0.025	1800	1.4 10^{-5}	0.138	0.136	0.002	0.007
Run 2	0.097	2100	4.6 10^{-5}	0.254	0.240	0.014	0.003
Run 3	0.022	1200	1.8 10^{-5}	0.338	0.323	0.015	0.001
TEST 3	(Shear stress increasing at 0.1 $N/m^2/hr$)						
Run 1	0.030	3600	8.3 10^{-6}	0.139	0.108	0.031	0.0003
Run 2	0.027	1800	1.5 10^{-5}	0.225	0.212	0.013	0.001
Run 3	0.038	2100	1.8 10^{-5}	0.280	0.259	0.021	0.0009
Run 4	0.044	2100	2.1 10^{-5}	0.344	0.344	0.0	–
TEST 4	(Shear stress increasing at 0.05 $N/m^2/hr$)						
Run 1	0.029	6900	4.2 10^{-6}	0.138	0.128	0.010	0.0004
Run 2	0.041	4200	1.0 10^{-5}	0.218	0.206	0.012	0.0008
Run 3	0.048	4200	1.1 10^{-5}	0.276	0.262	0.014	0.0008

TABLE 6: **Composition of mud/sand mixture beds for erosion tests**

Depth of suspension for all tests	0.113 m
Concentration of mud in suspension for all tests	30.3 kg/m^3
Salinity for all tests	35.7 kg/m^3
Total consolidation period for all tests	3 days

TEST NO	CONCENTRATION OF MUD IN SUSPENSION (kg/m^3)	TOTAL MASS OF SAND ADDED (kg)	TIME OF ADDITION OF SAND	SAND CONTENT IN TOP 5mm OF BED (% dry weight of total)	BED THICKNESS AFTER 3 DAYS (mm)
1	30.3	7.0	50% after 6hrs 50% after 11 hrs	66	12.2
2	30.3	3.5	100% after 7hrs	50	14.1
3	30.3	0.9	100% after 7hrs	20	14.2
4	30.3	0.45	100% after 7hrs	11	14.2
5	30.3	0.0	-	0	16.8

TABLE 7: Details of runs in mud/sand erosion tests

TEST NO	NUMBER OF RUNS BEFORE MASS EROSION	ROOF ROTATION SPEED (rpm)					TEMPERATURE (°C)
		Run 1	Run 2	Run 3	Run 4	Run 5	
1	5	2.17	2.52	2.86	3.21	3.53	10.9
2	4	2.17	2.52	2.86	3.21		11.3
3	2	2.17	2.52				14.4
4	3	2.17	2.52	2.86			10.7
5	3	2.17	2.52	2.86			9.1

FIGURES.

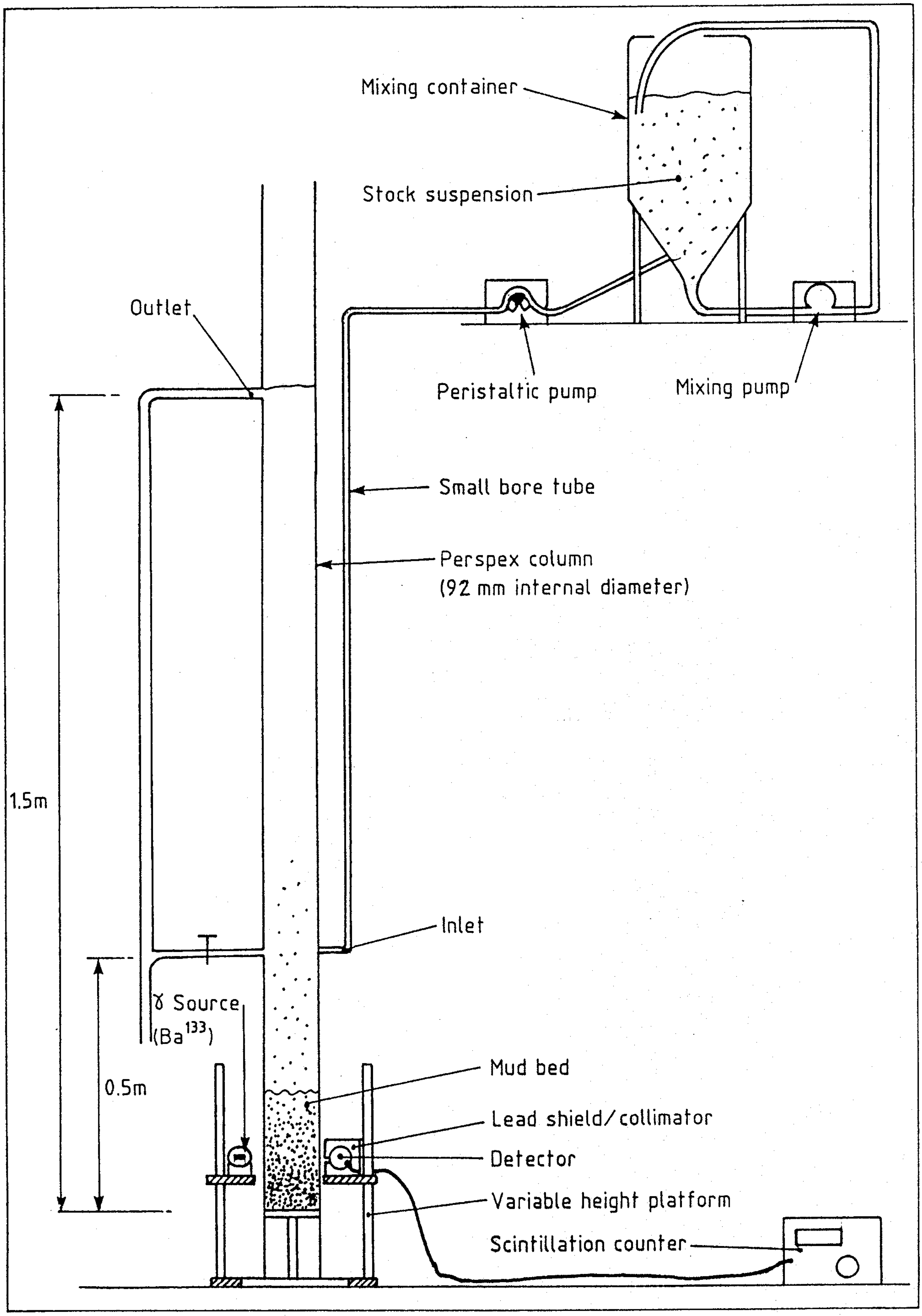

Fig 1 Settling column apparatus.

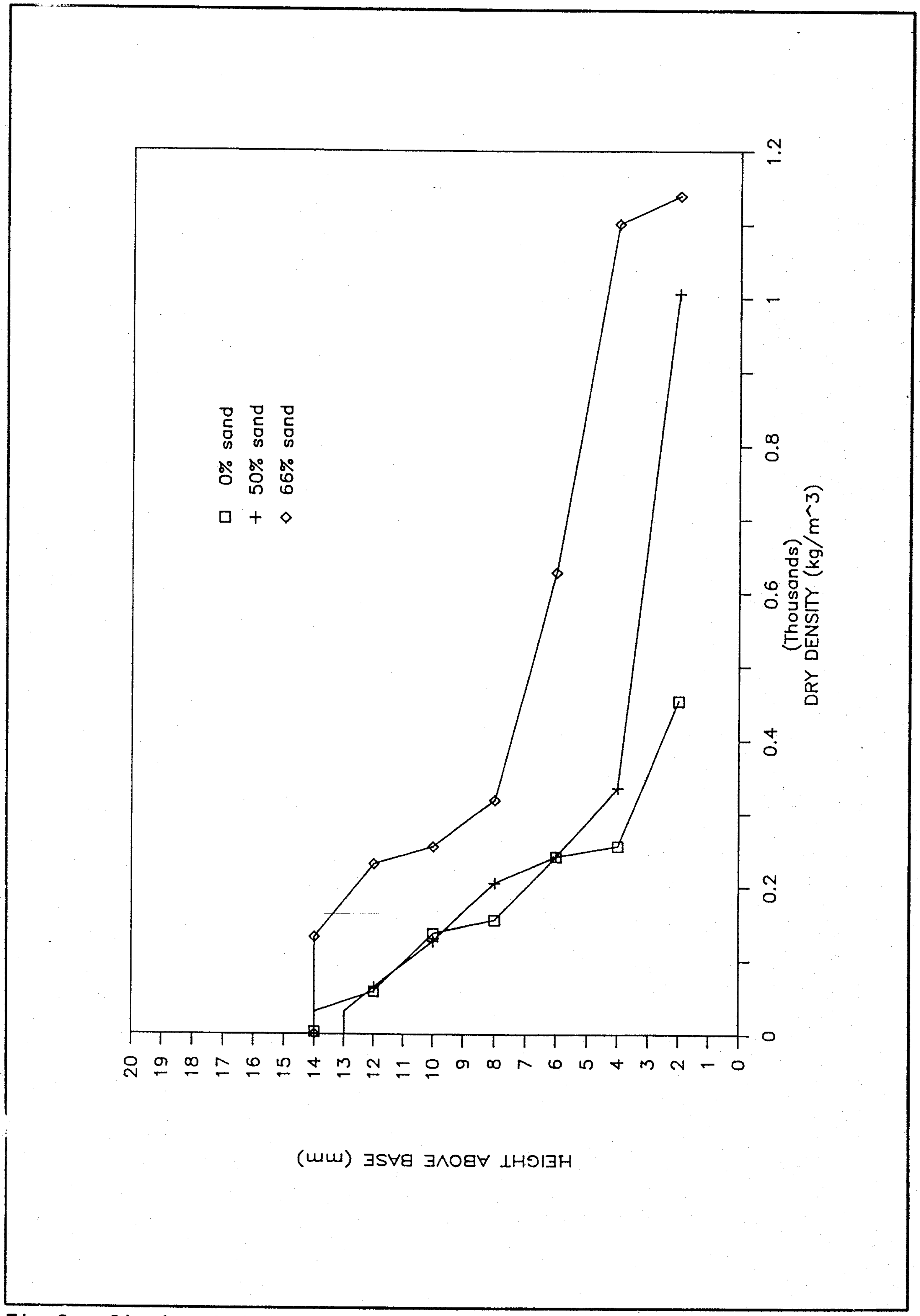

Fig 2 Single shot tests Final density profiles, 20mm beds

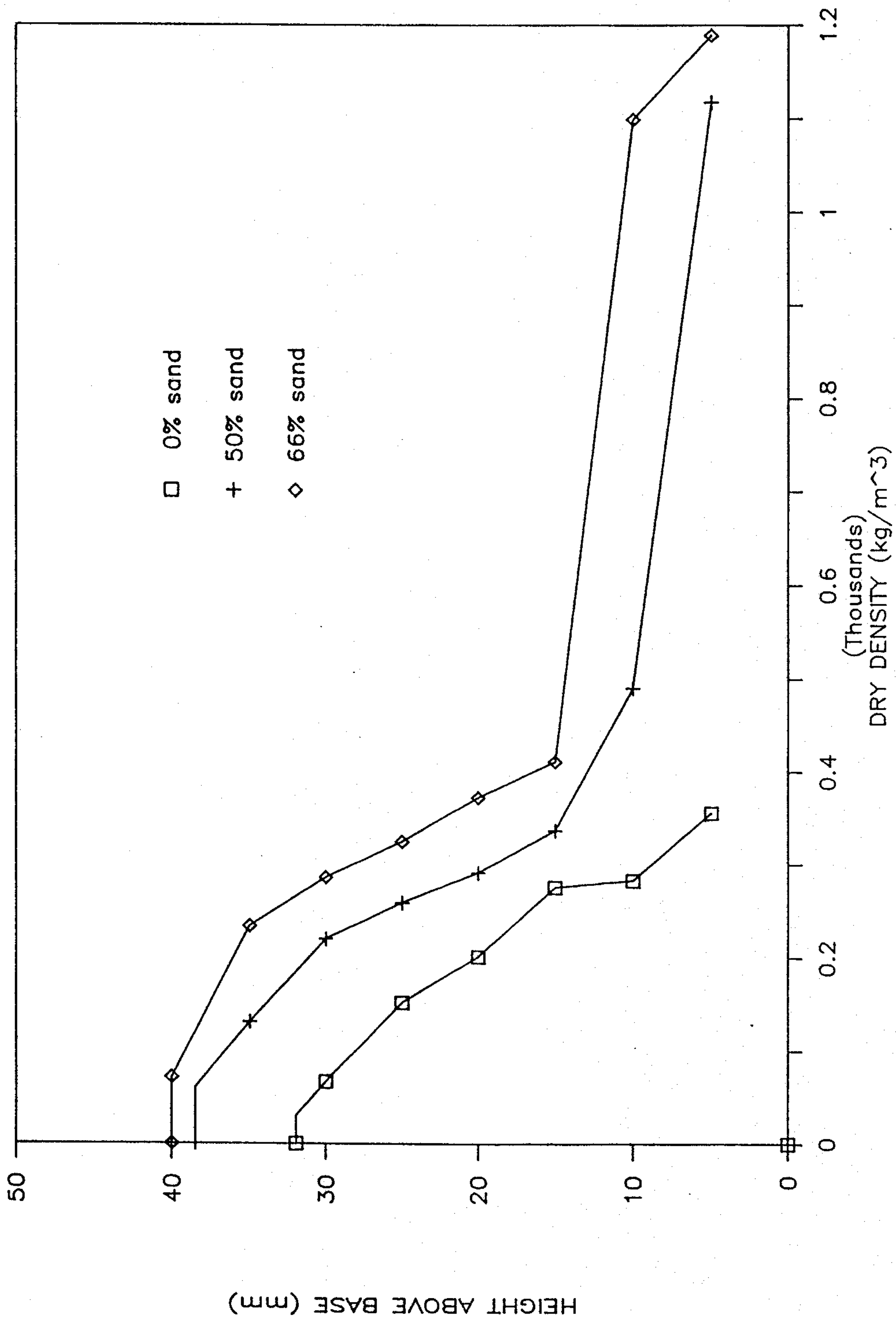

Fig 3 Single shot tests Final density profiles, 50mm beds

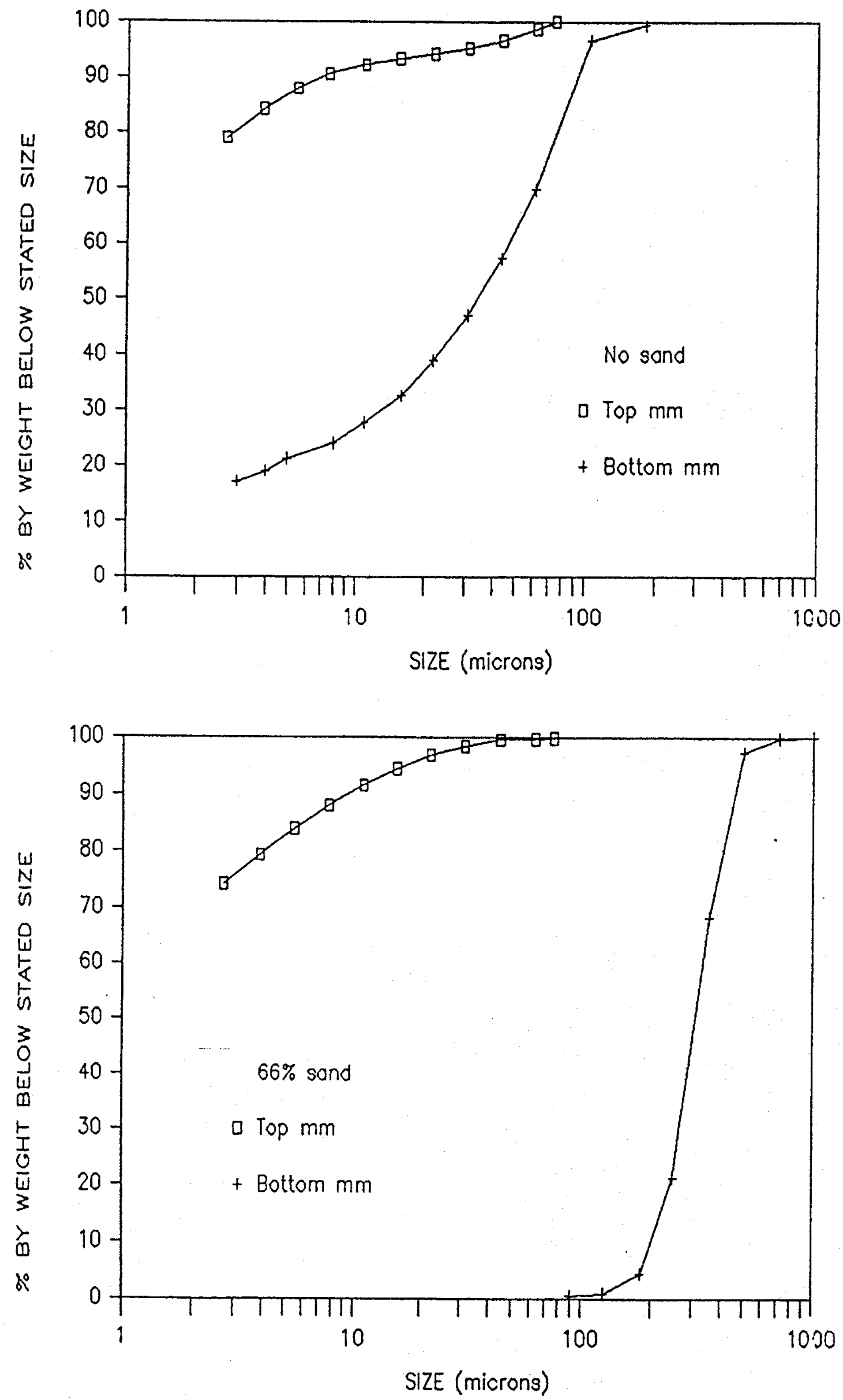

Fig 4 Single shot tests Size gradings from the top mm and bottom mm of the bed

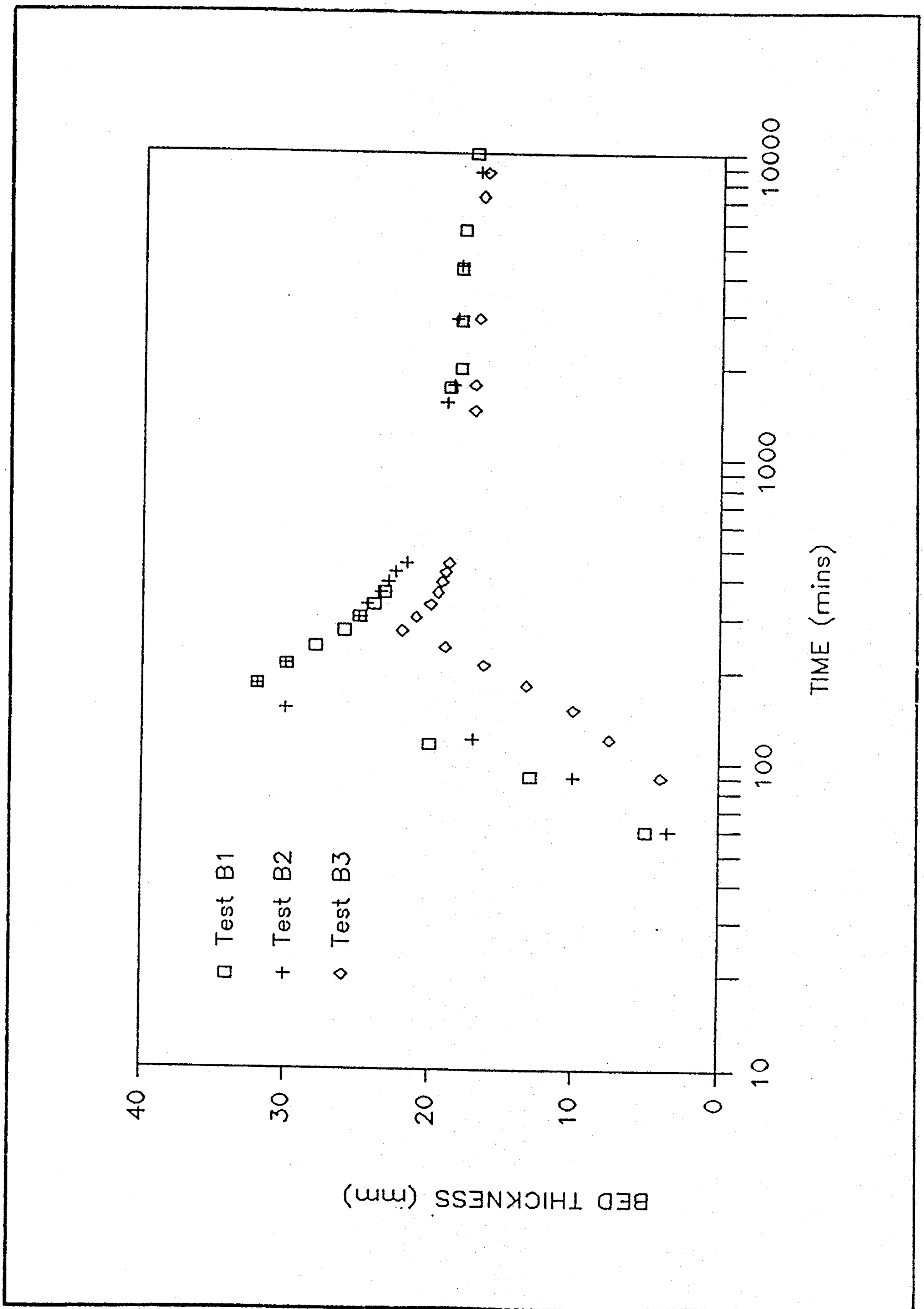

Fig 5 Continuous deposition tests, mud only Variation of bed thickness with time

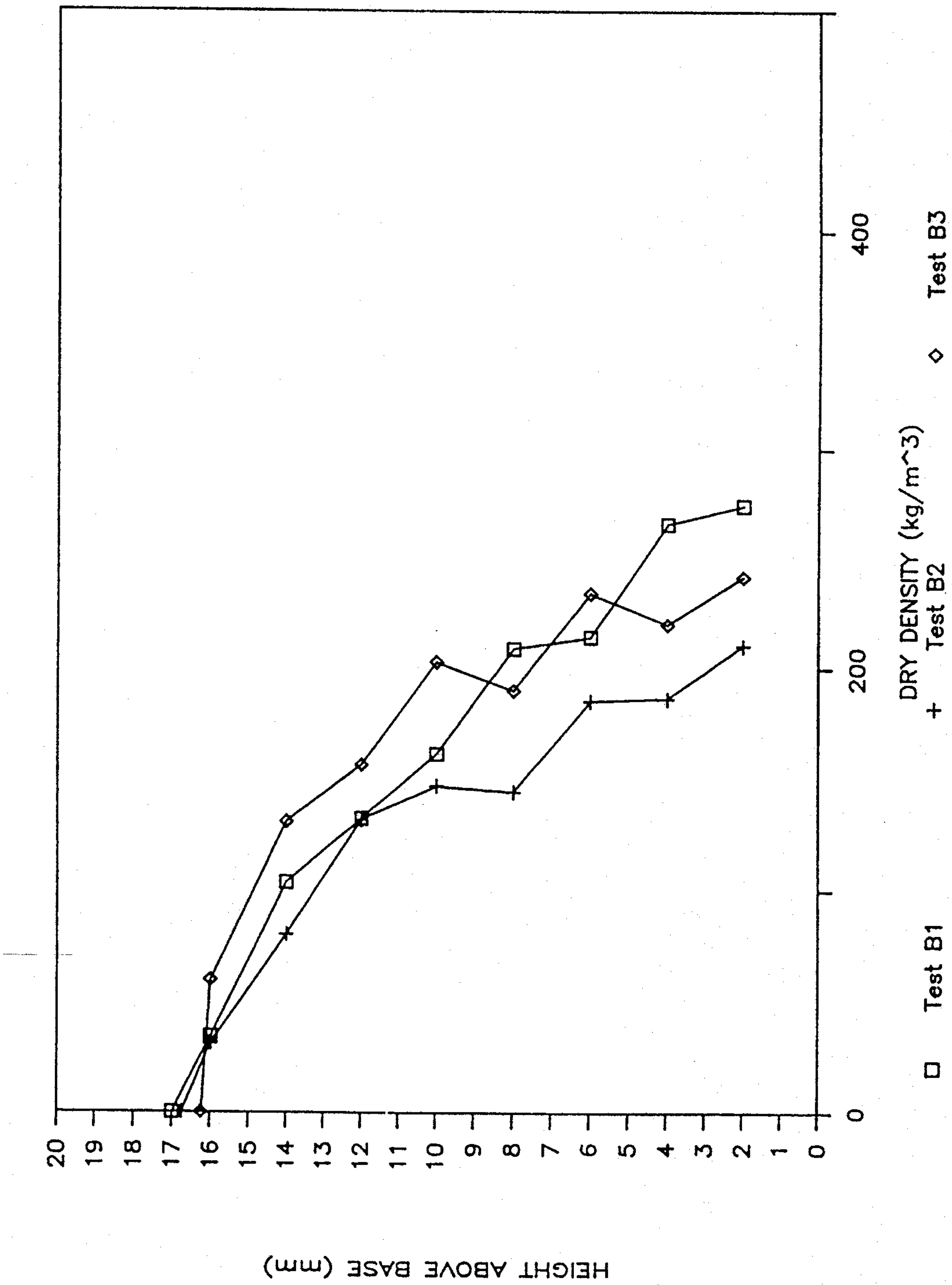

Fig 6 Continuous deposition tests, mud only Final density profiles, 20mm beds

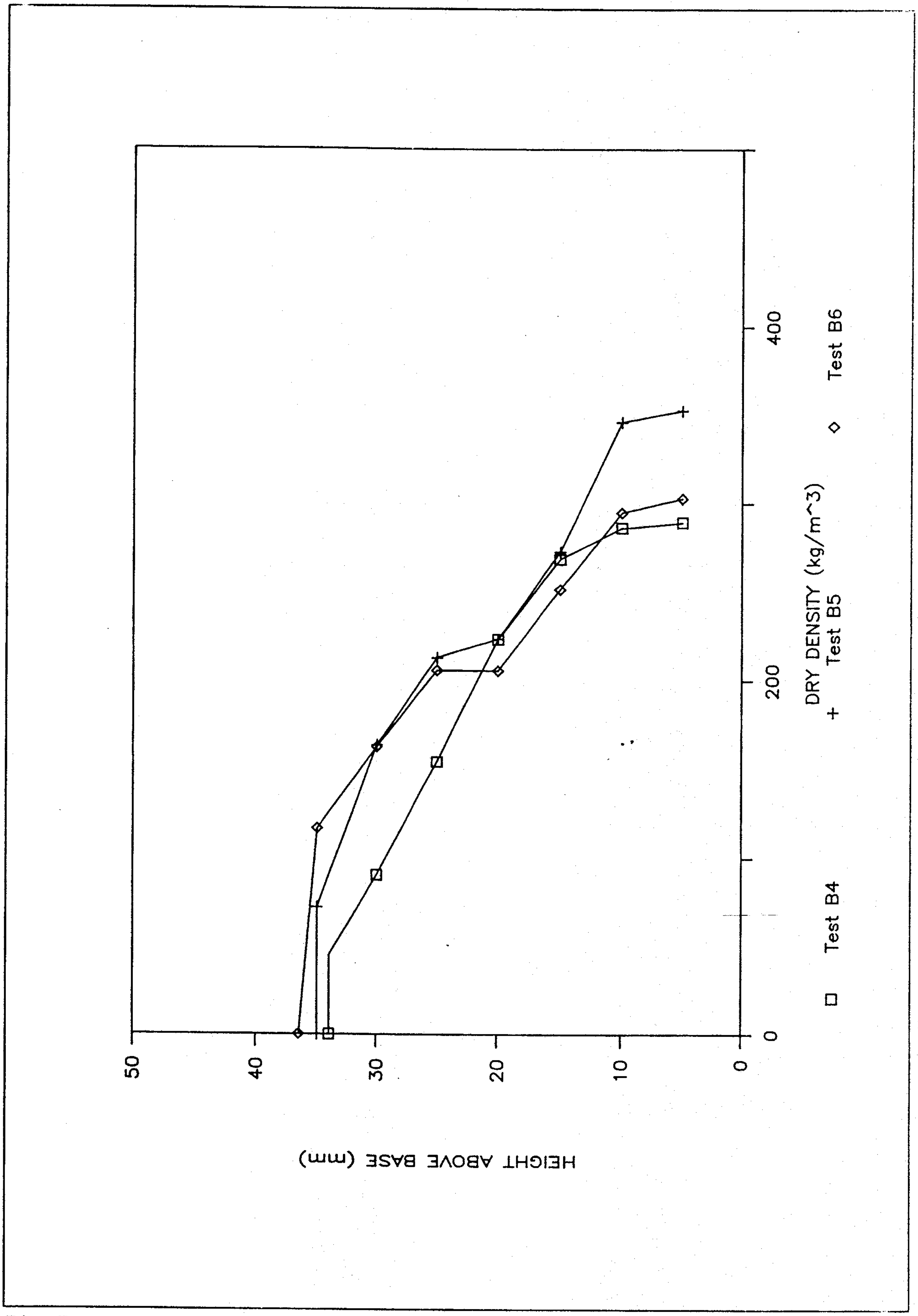

Fig 7 Continuous deposition tests, mud only Final density profiles, 50mm beds

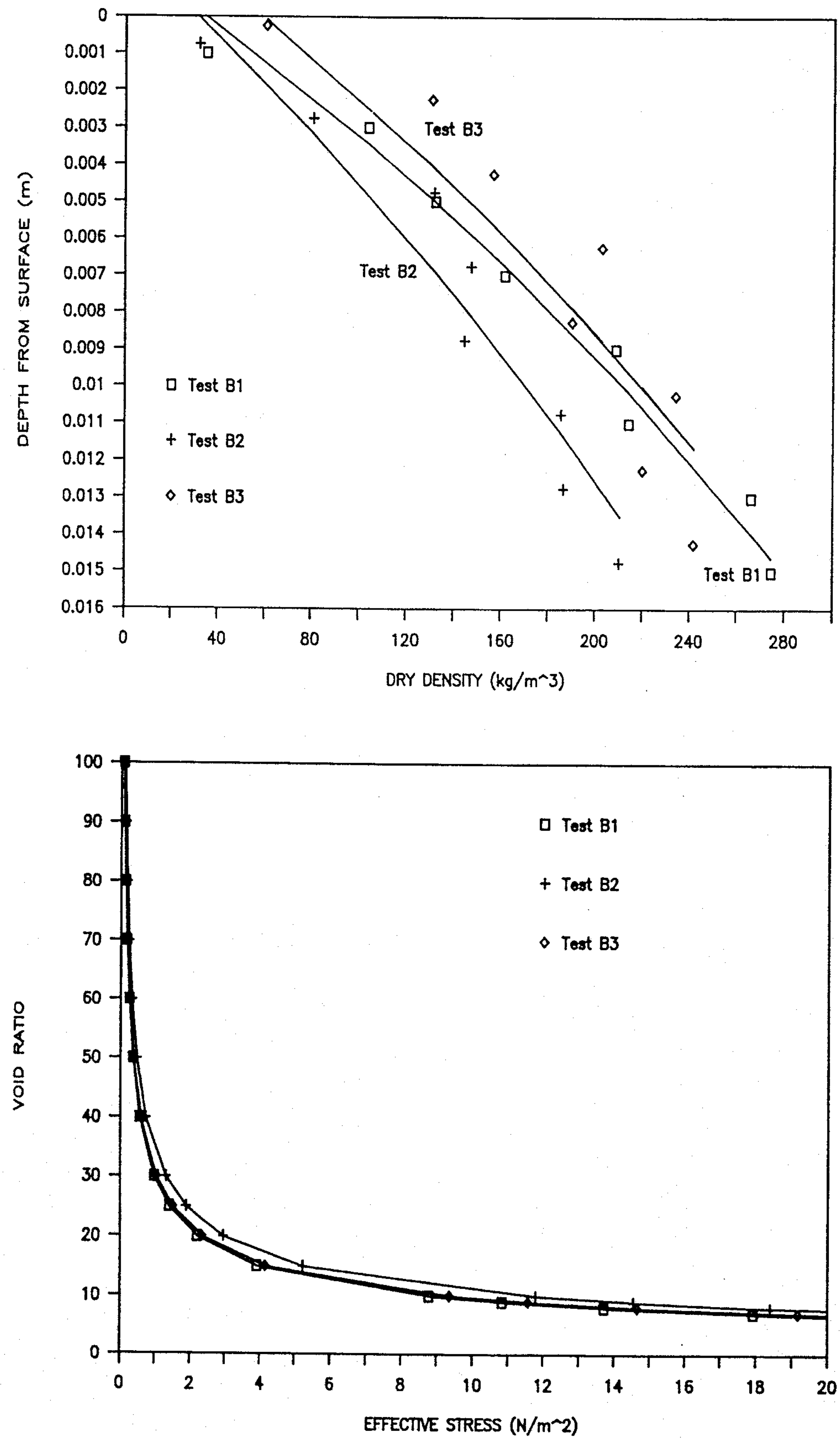

Fig 8 Continuous deposition, mud only Final density against depth and effective stress against voids ratio, 20mm beds

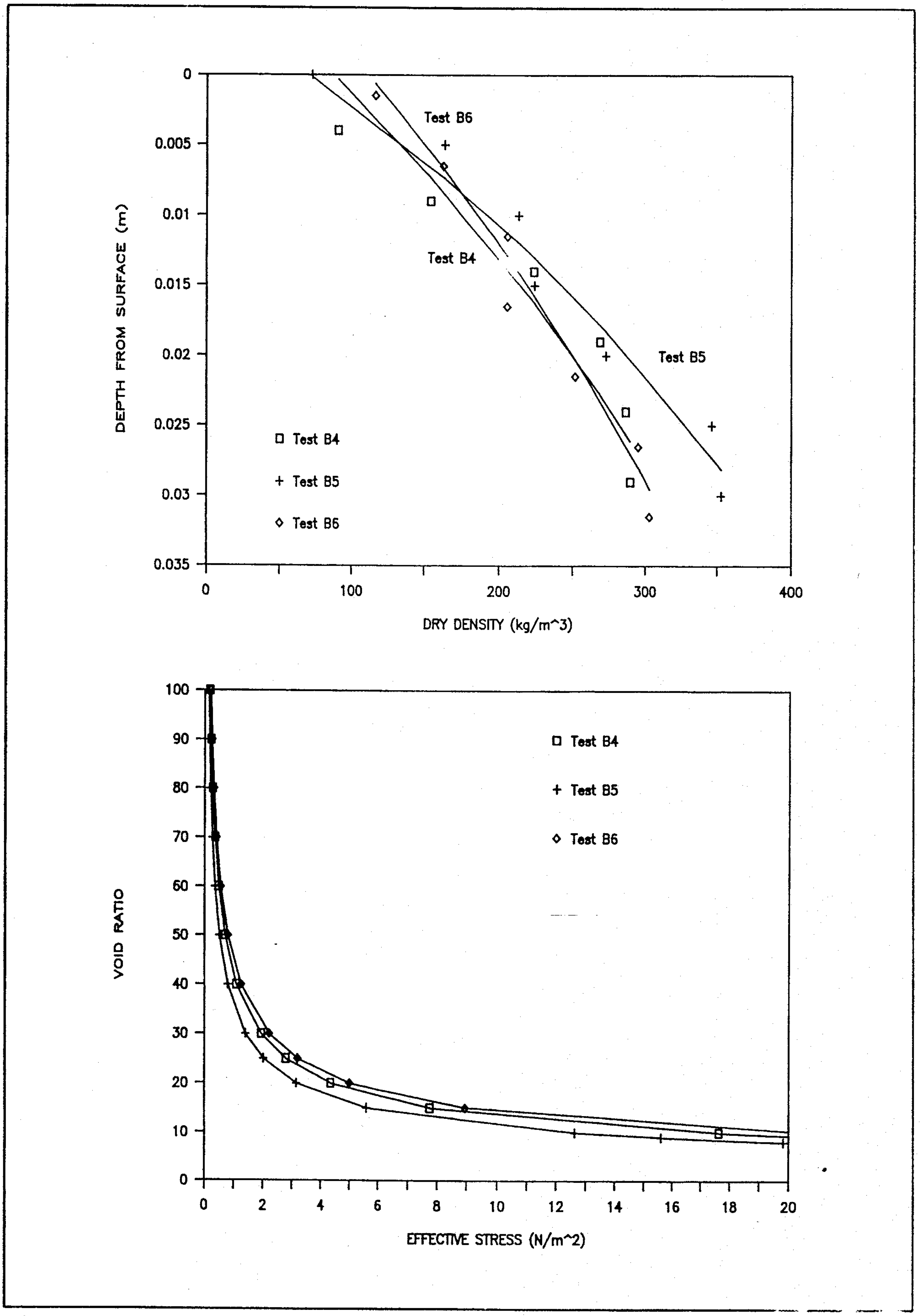

Fig 9 Continuous deposition, mud only Final density against depth and effective stress against voids ratio, 50mm beds

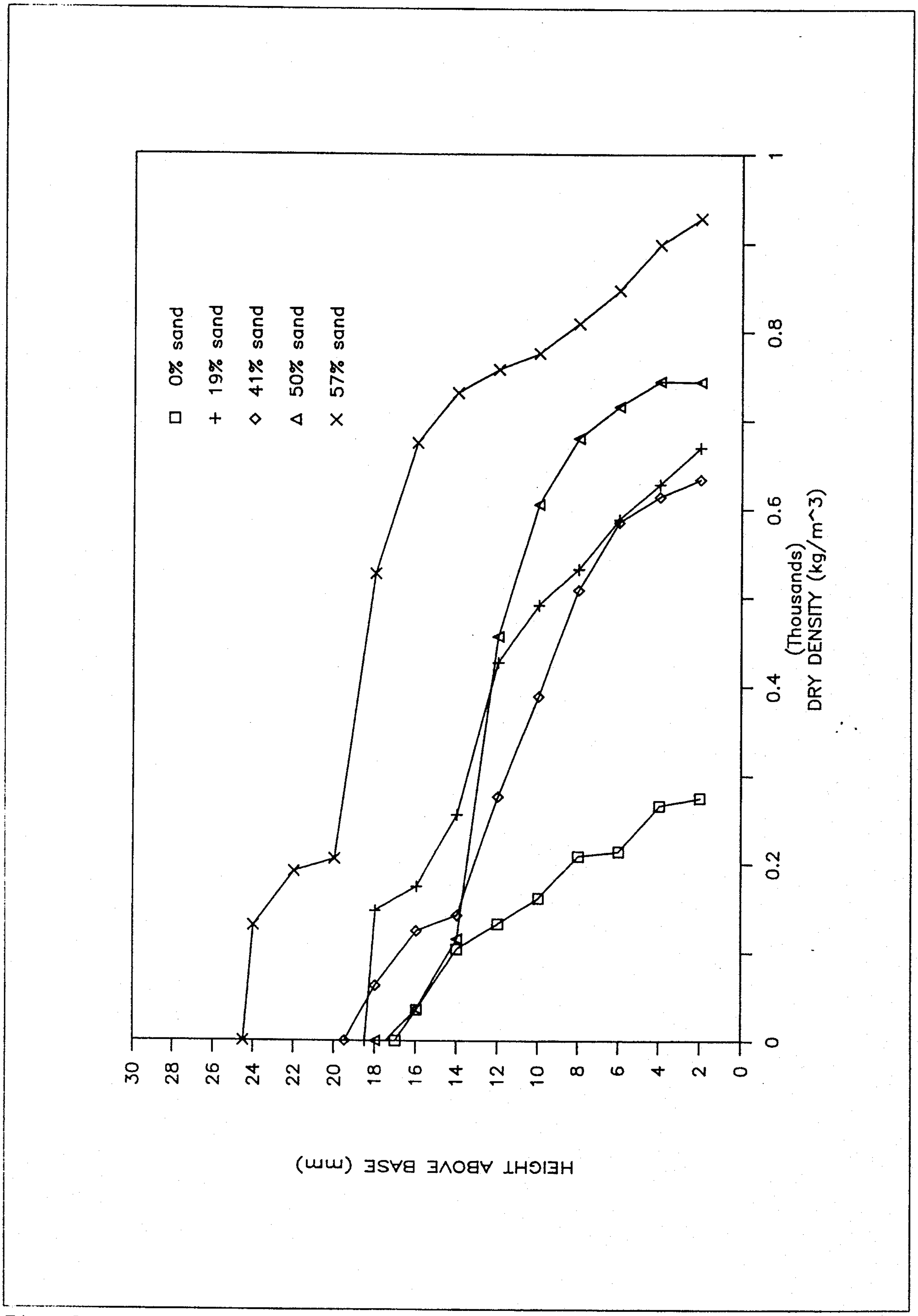

Fig 10 Continuous deposition tests, mud/sand Final density profiles, 20mm beds

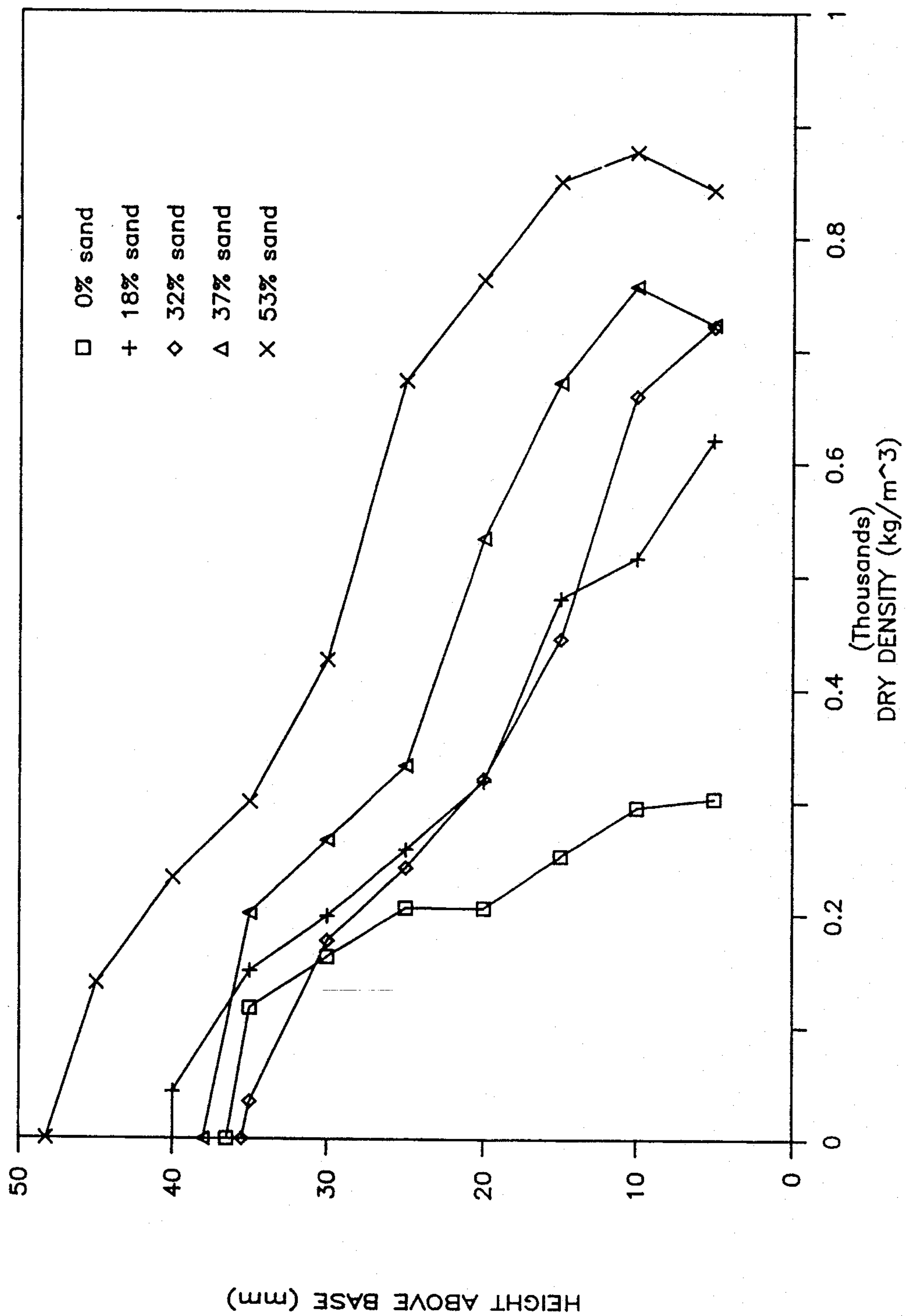

Fig 11 Continuous deposition tests, mud/sand Final density profiles, 50mm beds

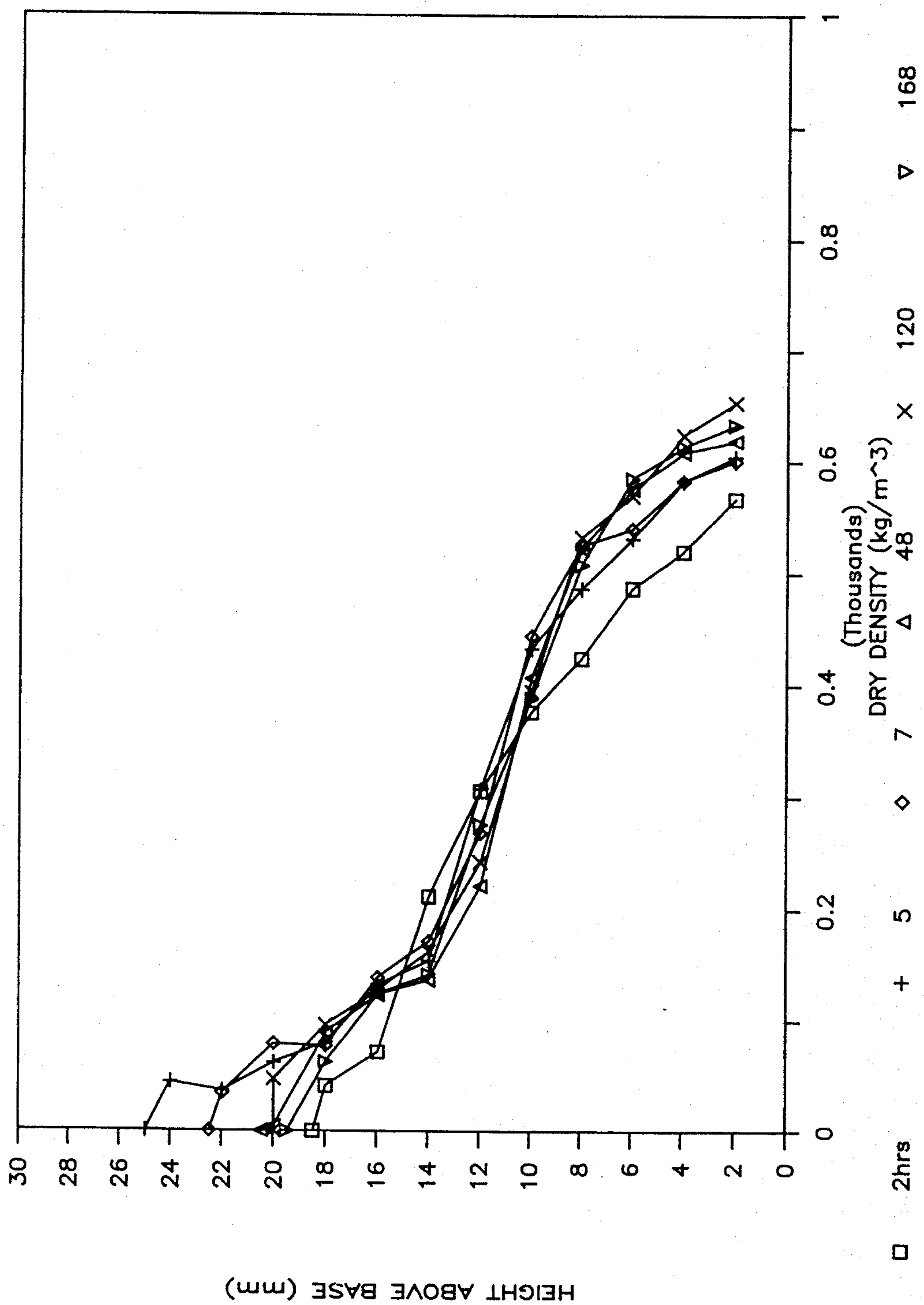

Fig 12 Continuous deposition test C2, 19% sand Density profiles with time

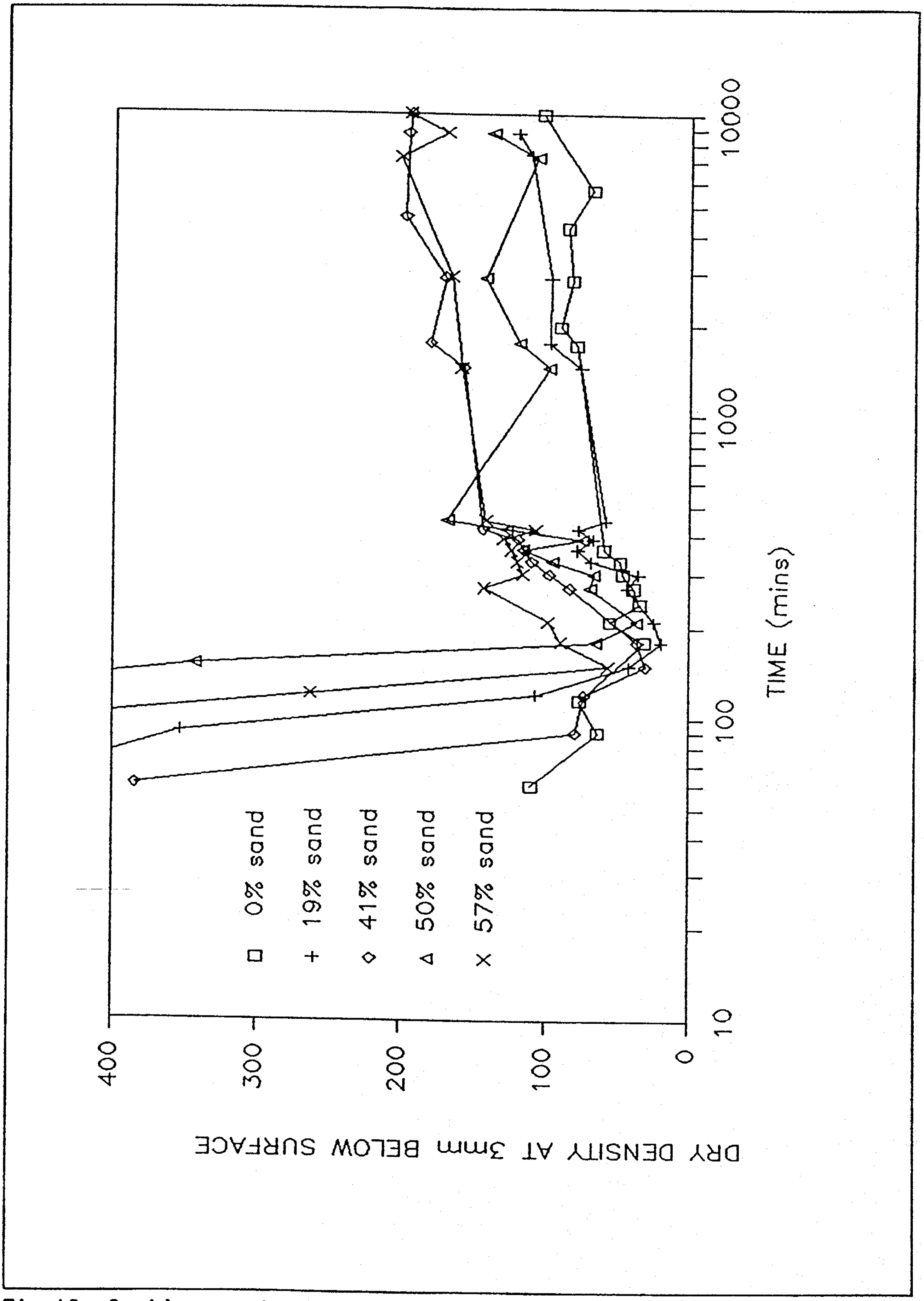

Fig 13 Continuous deposition tests, mud/sand Near-surface density with time, 20mm beds

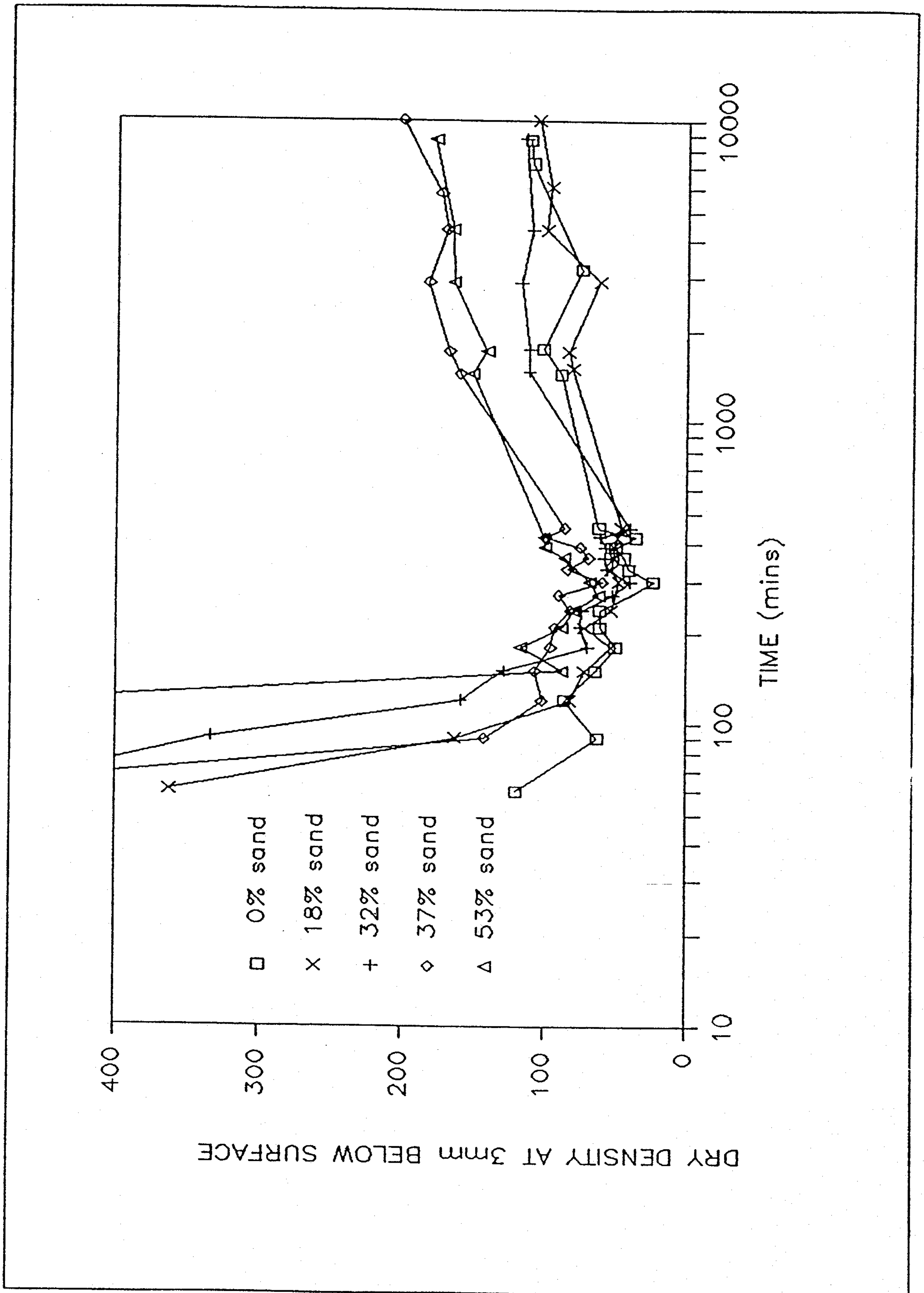

Fig 14 Continuous deposition tests, mud/sand Near-surface density with time, 50mm beds

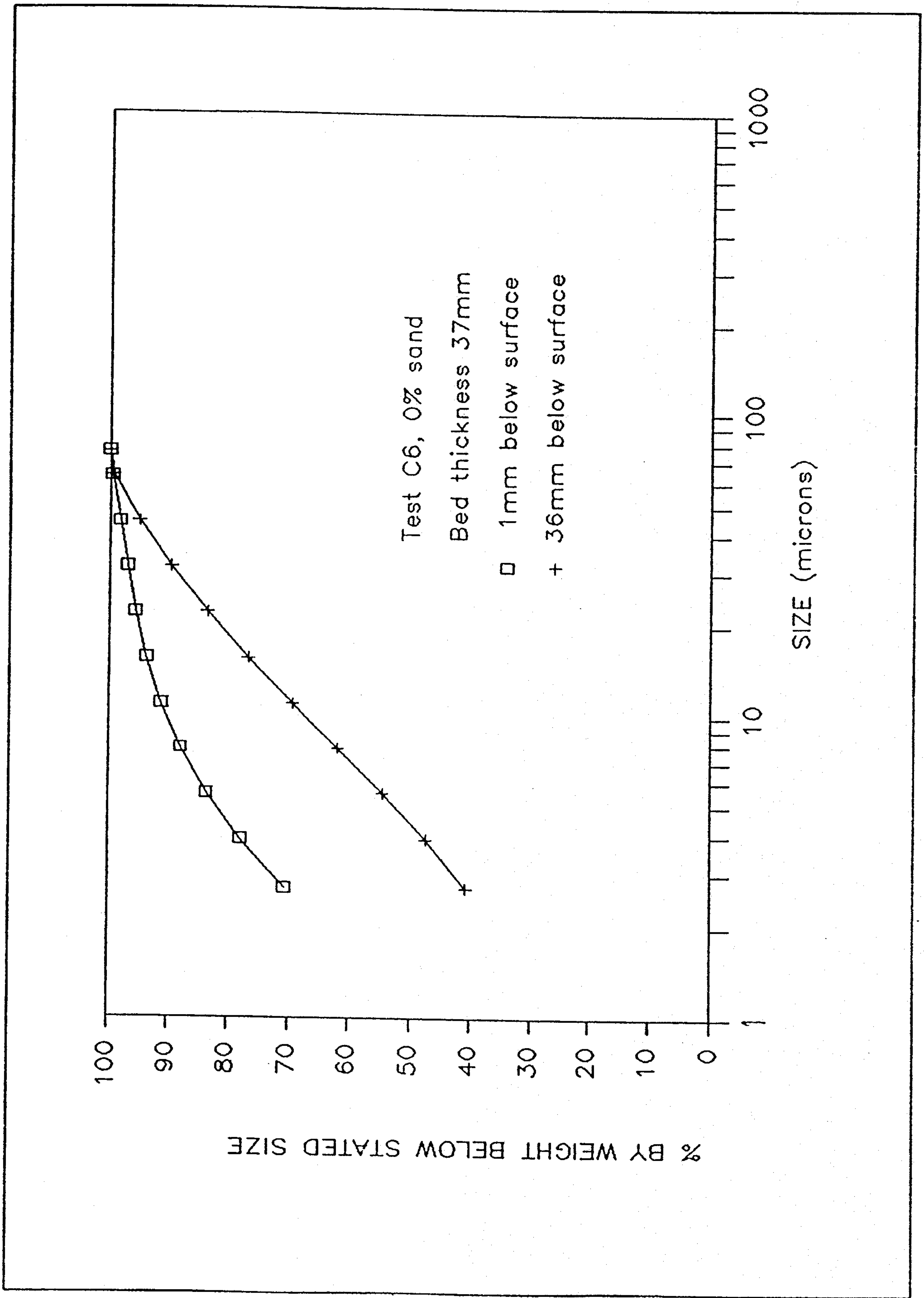

Fig 15 Continuous deposition tests, mud/sand Size gradings from the top mm and bottom mm of the bed, 0% sand

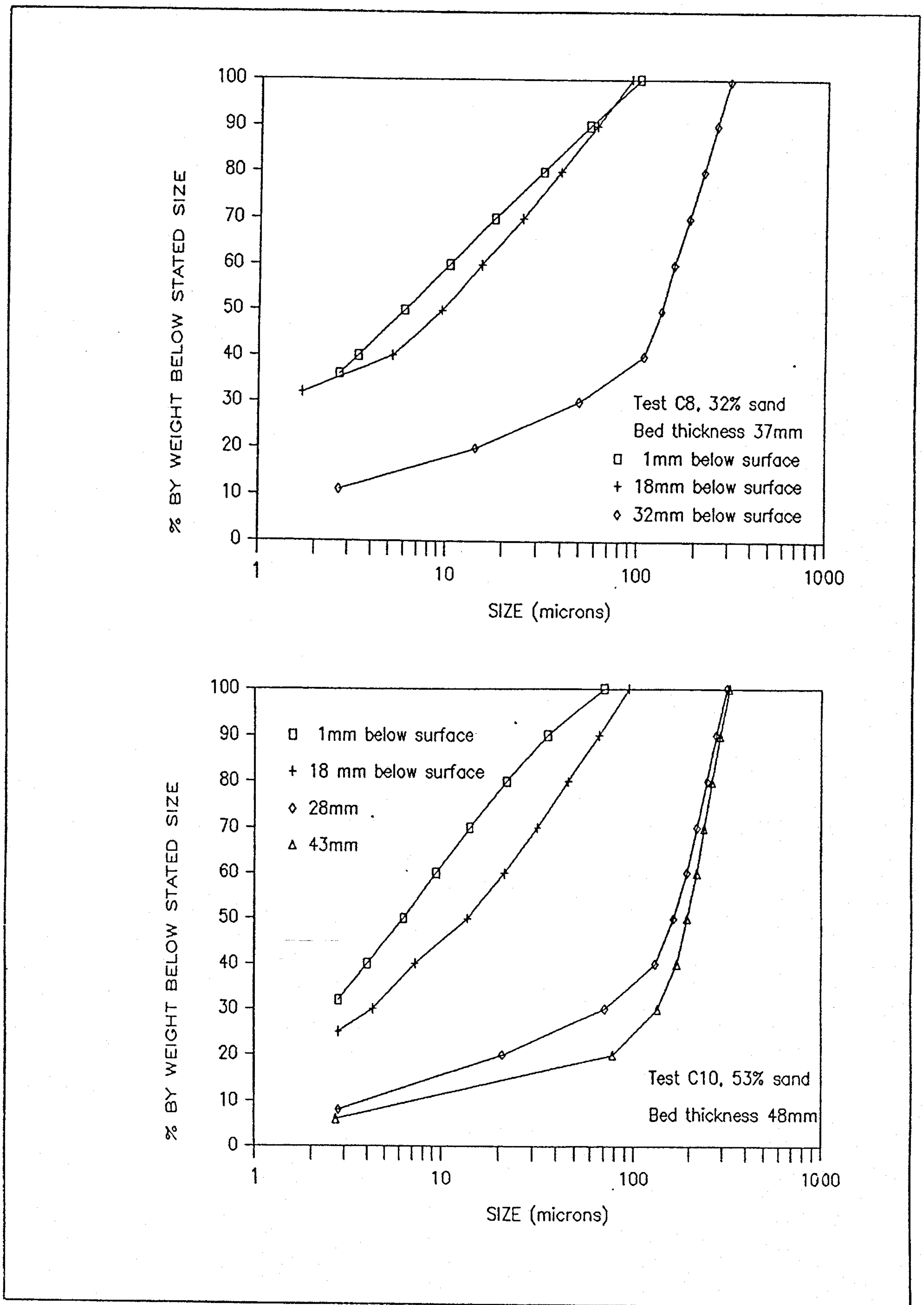

Fig 16 Continuous deposition tests, mud/sand Size gradings from various points in the bed, 32% sand and 53% sand

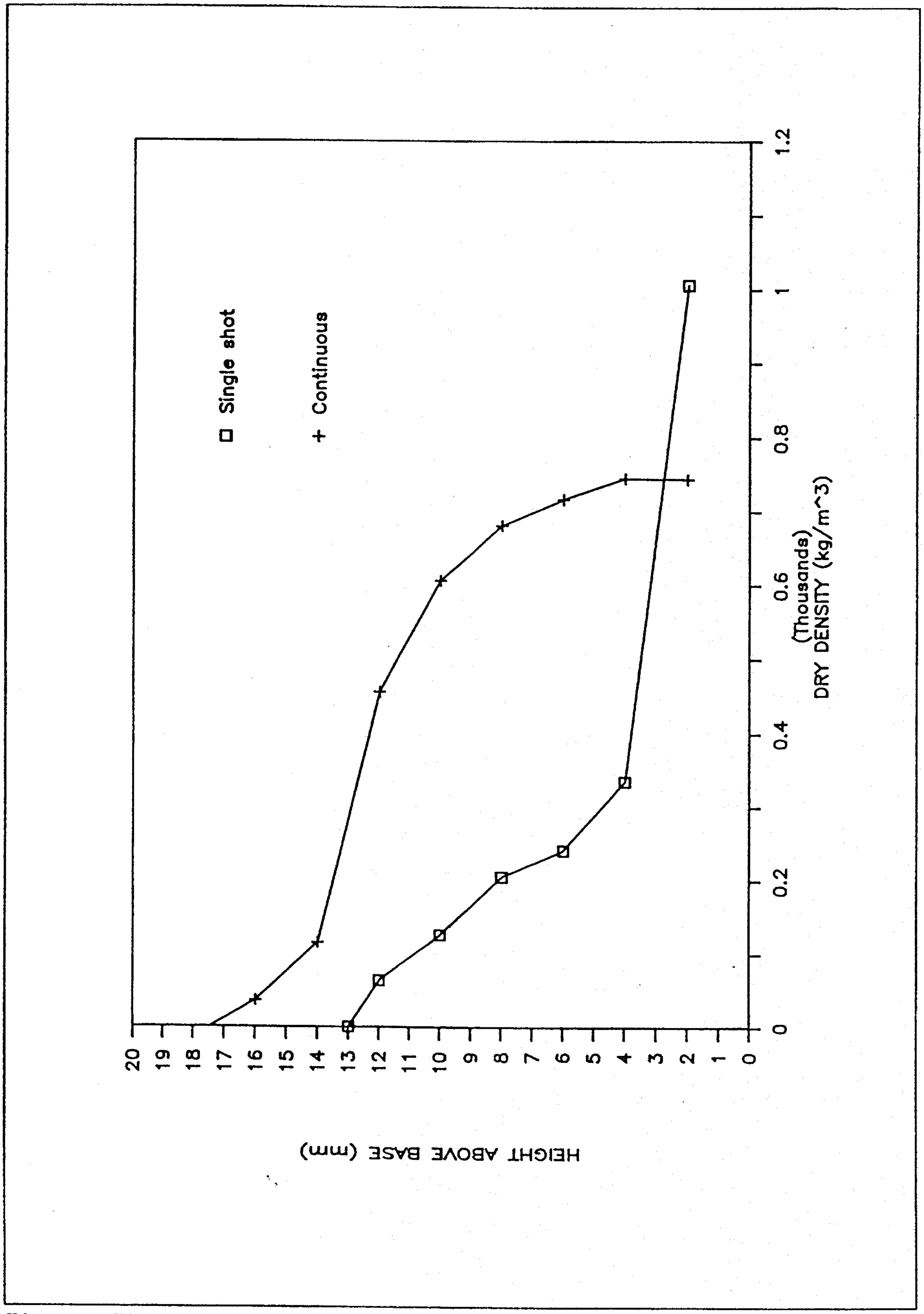

Fig 17 Final density profiles for single shot test A2 and continuous deposition test C4, 50% sand

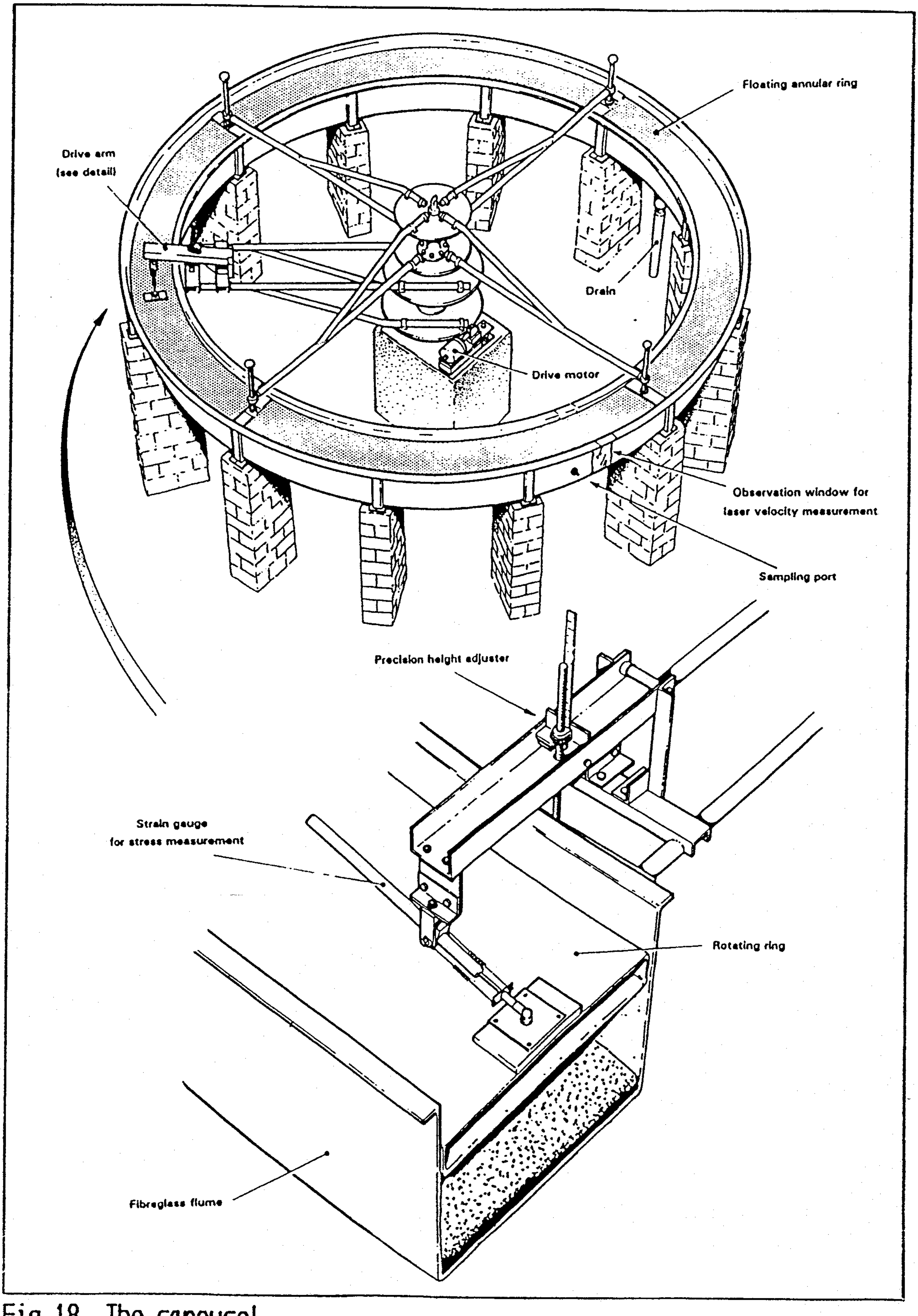

Fig 18 The carousel

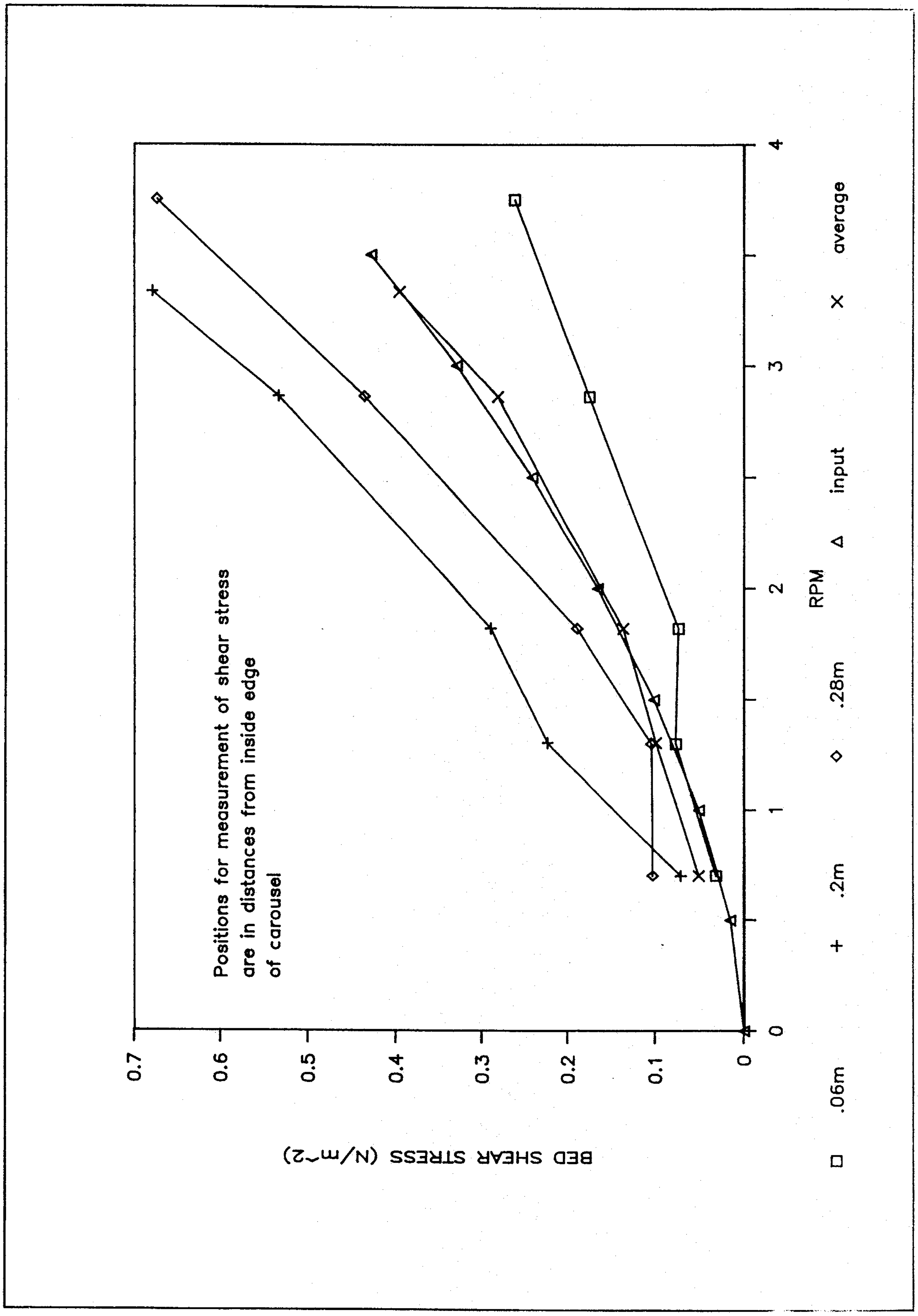

Fig 19 Average bed shear stress against roof speed

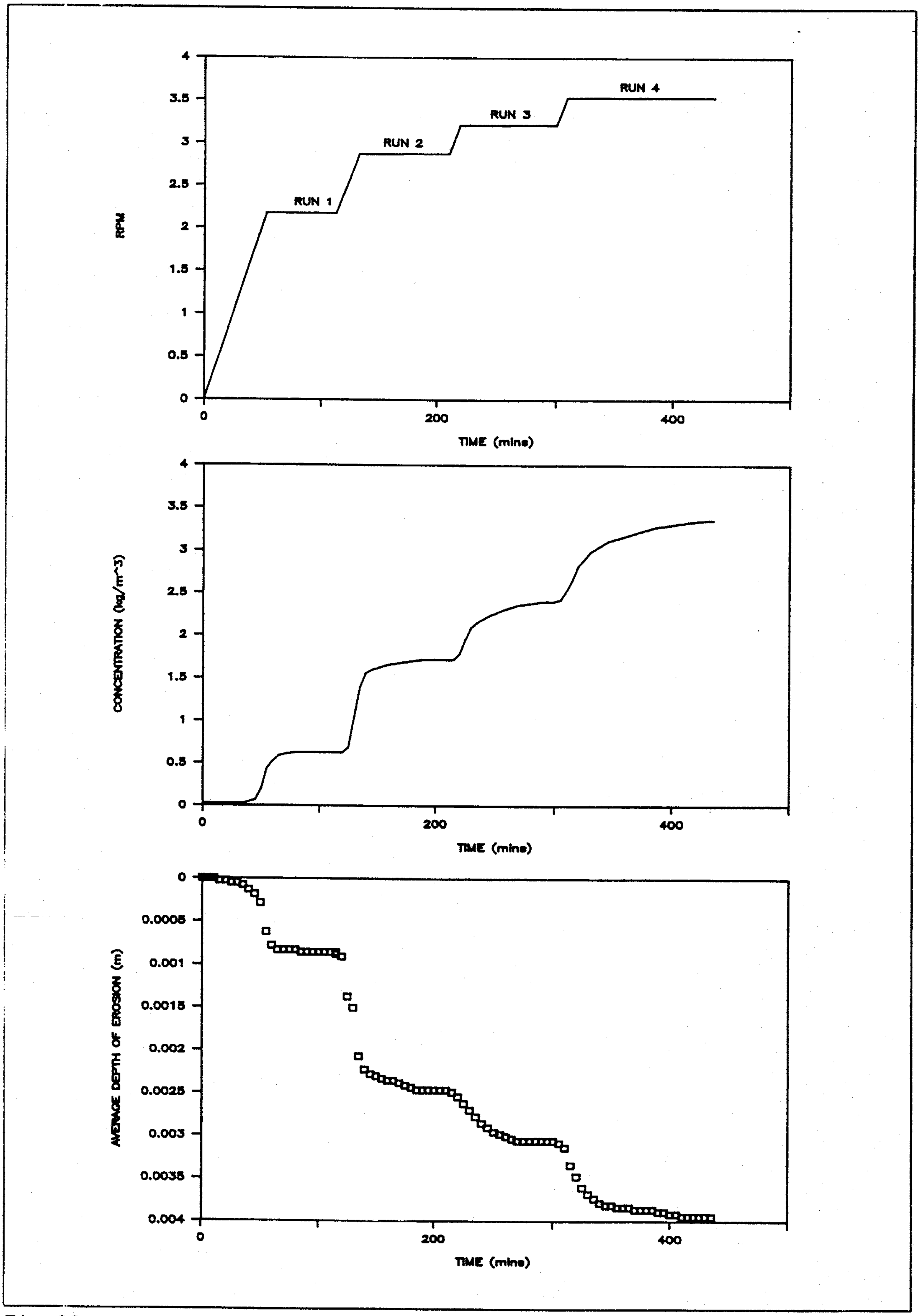

Fig 20 Roof speed, suspended solids concentration and depth of erosion, mud erosion Test 1

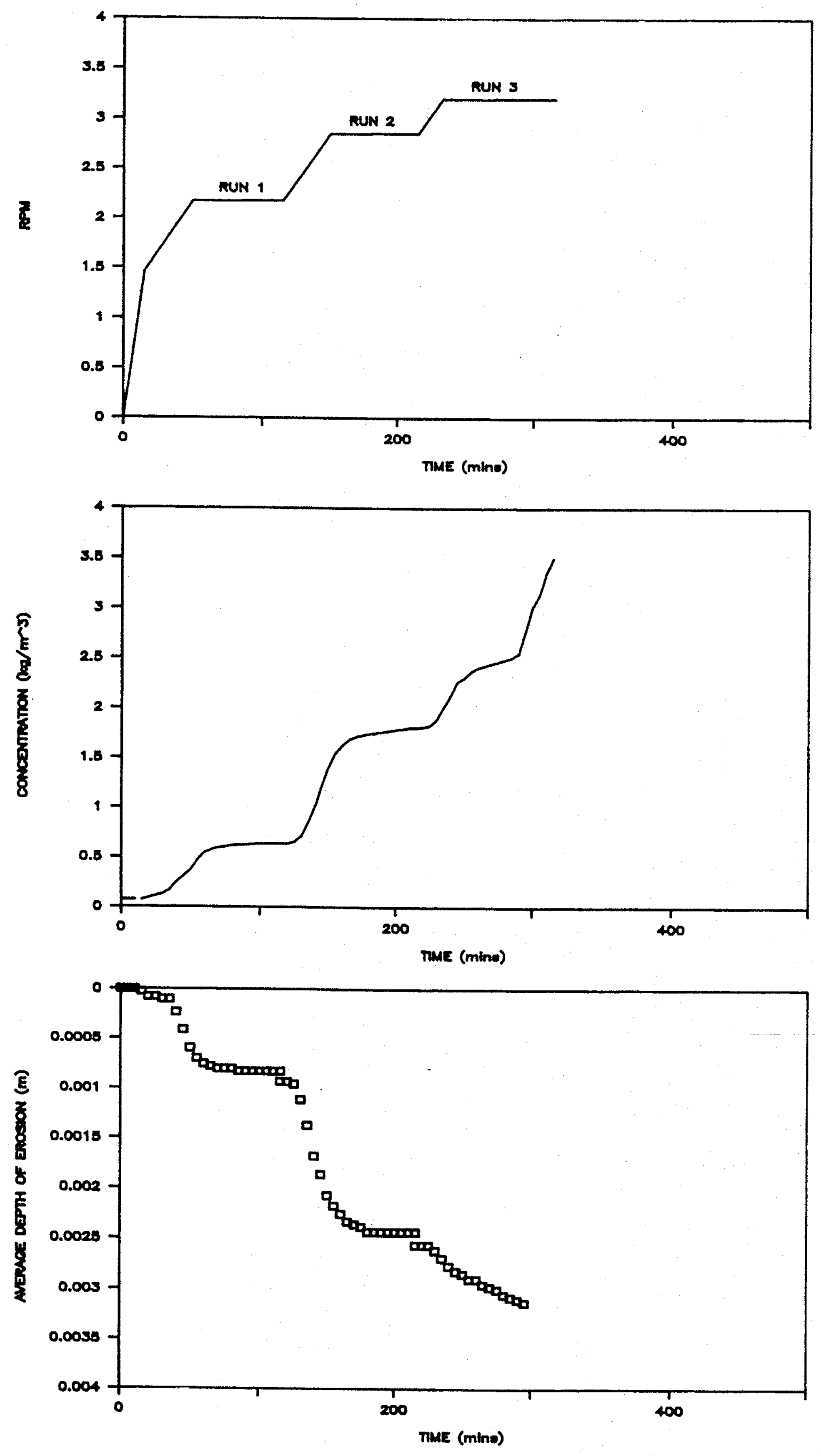

Fig 21 Roof speed, suspended solids concentration and depth of erosion, mud erosion Test 2

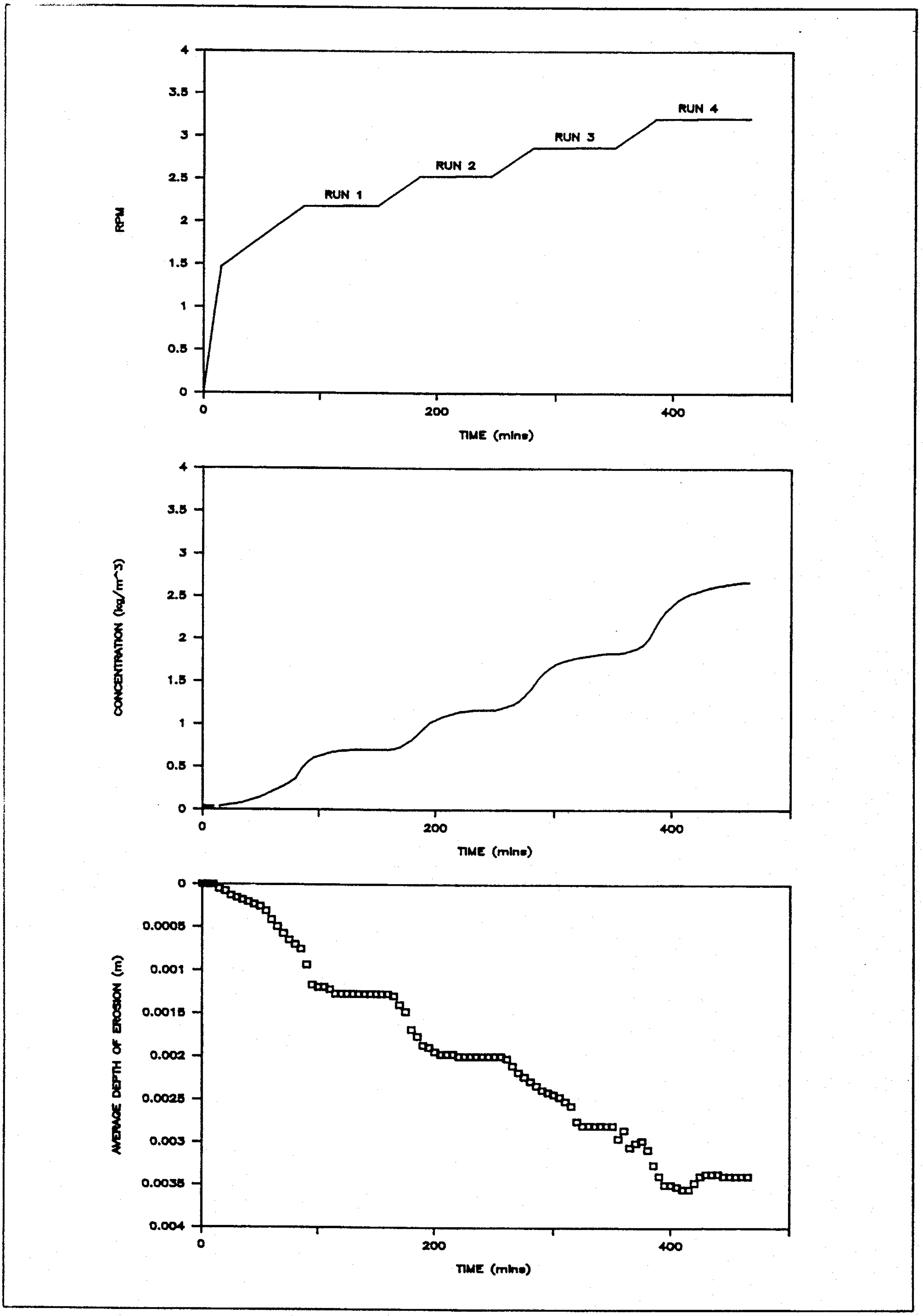

Fig 22 Roof speed, suspended solids concentration and depth of erosion, mud erosion Test 3

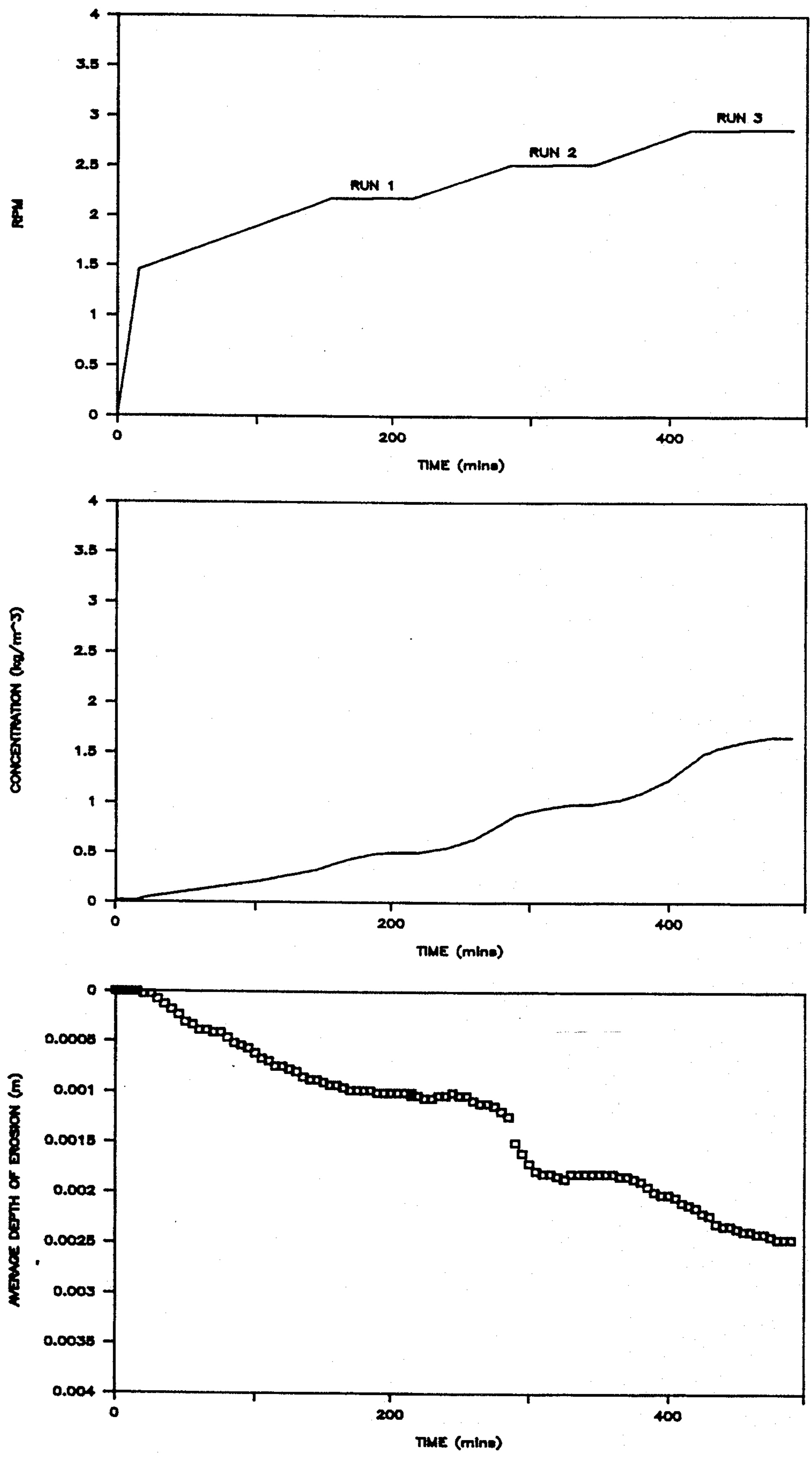

Fig 23 Roof speed, suspended solids concentration and depth of erosion, mud erosion Test 4

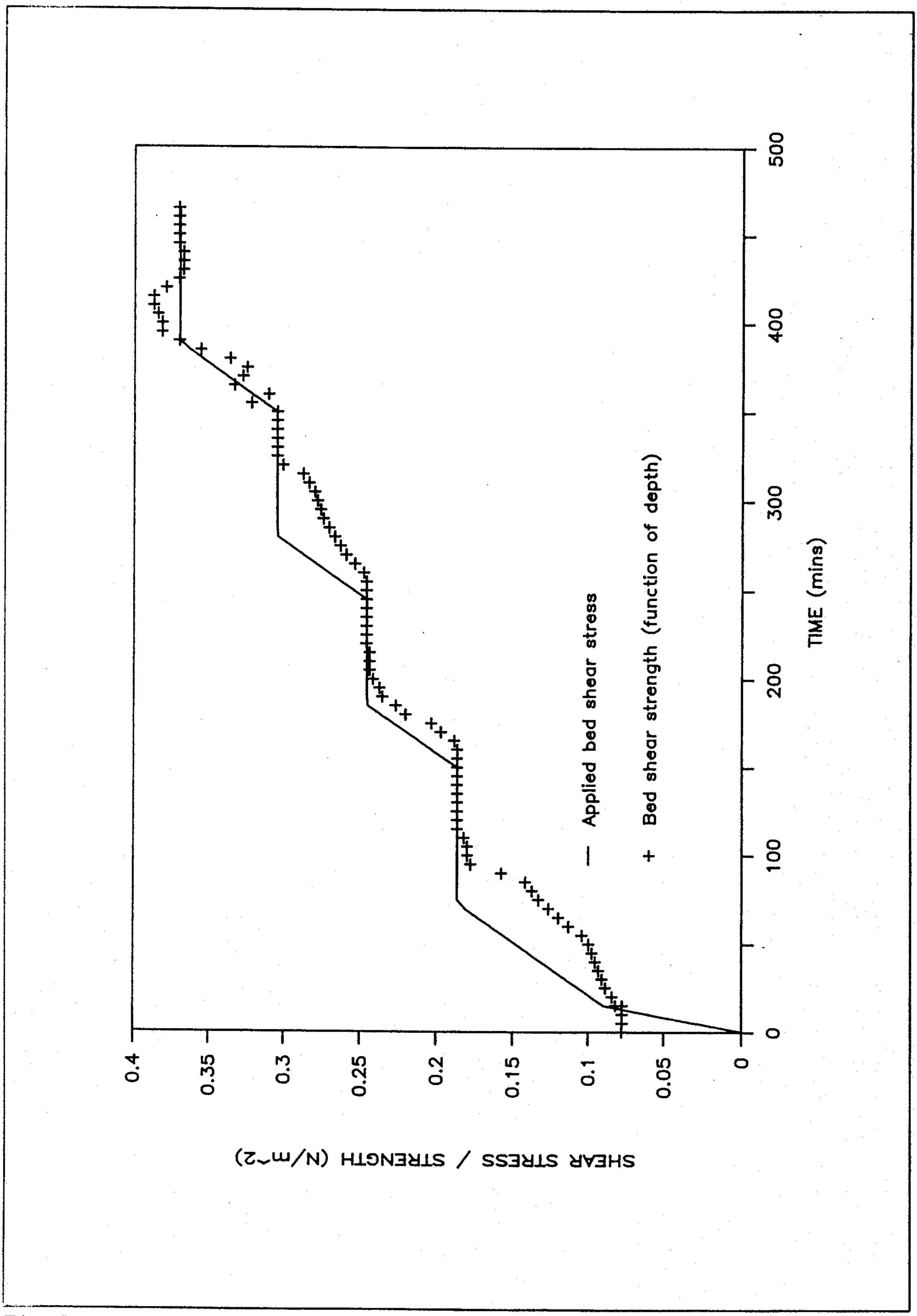

Fig 24 Applied bed shear stress and bed shear strength, mud erosion Test 3

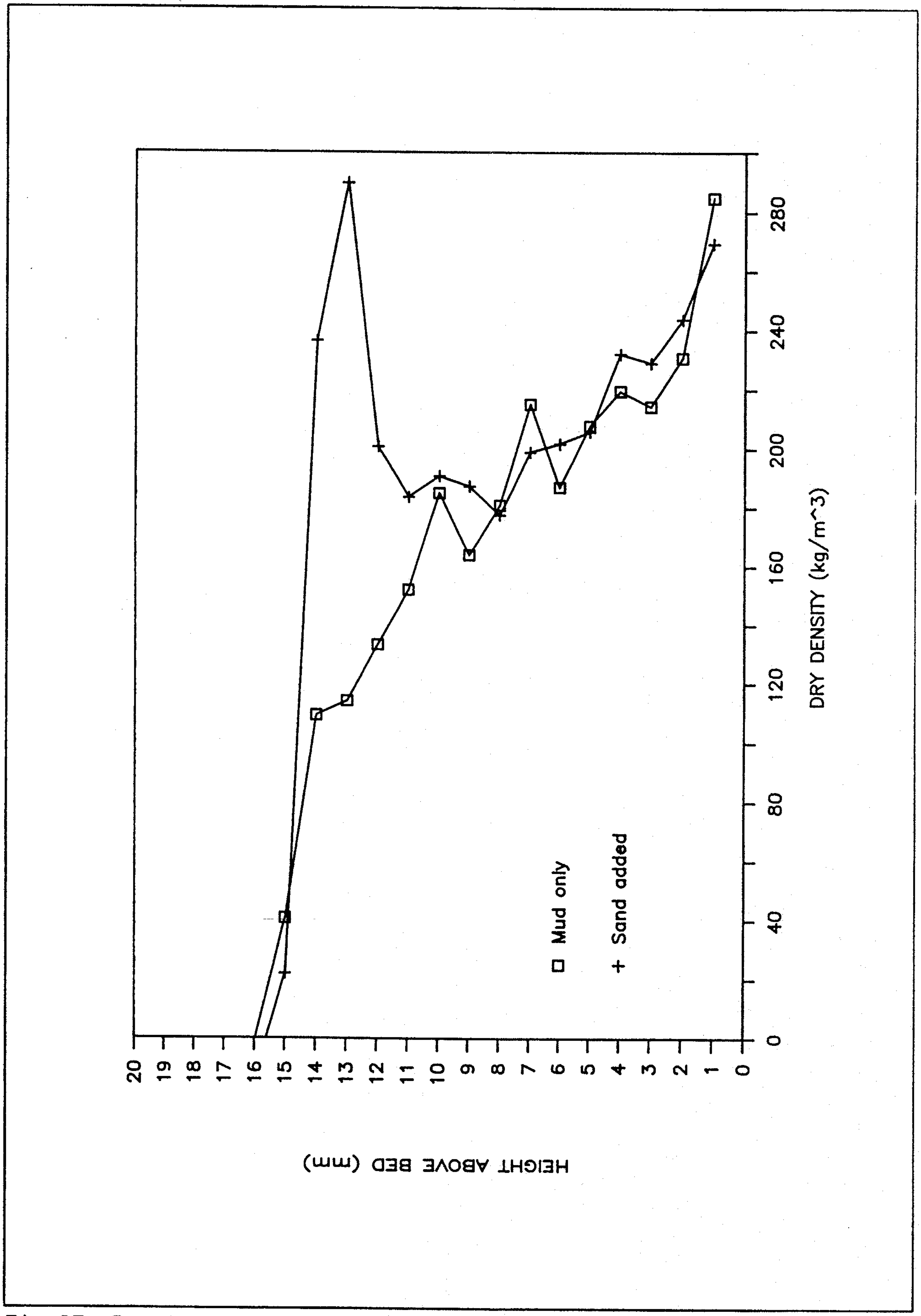

Fig 25 Density profile of mud bed and mud/sand bed after 3 days consolidation. 50% sand in top 5mm of bed

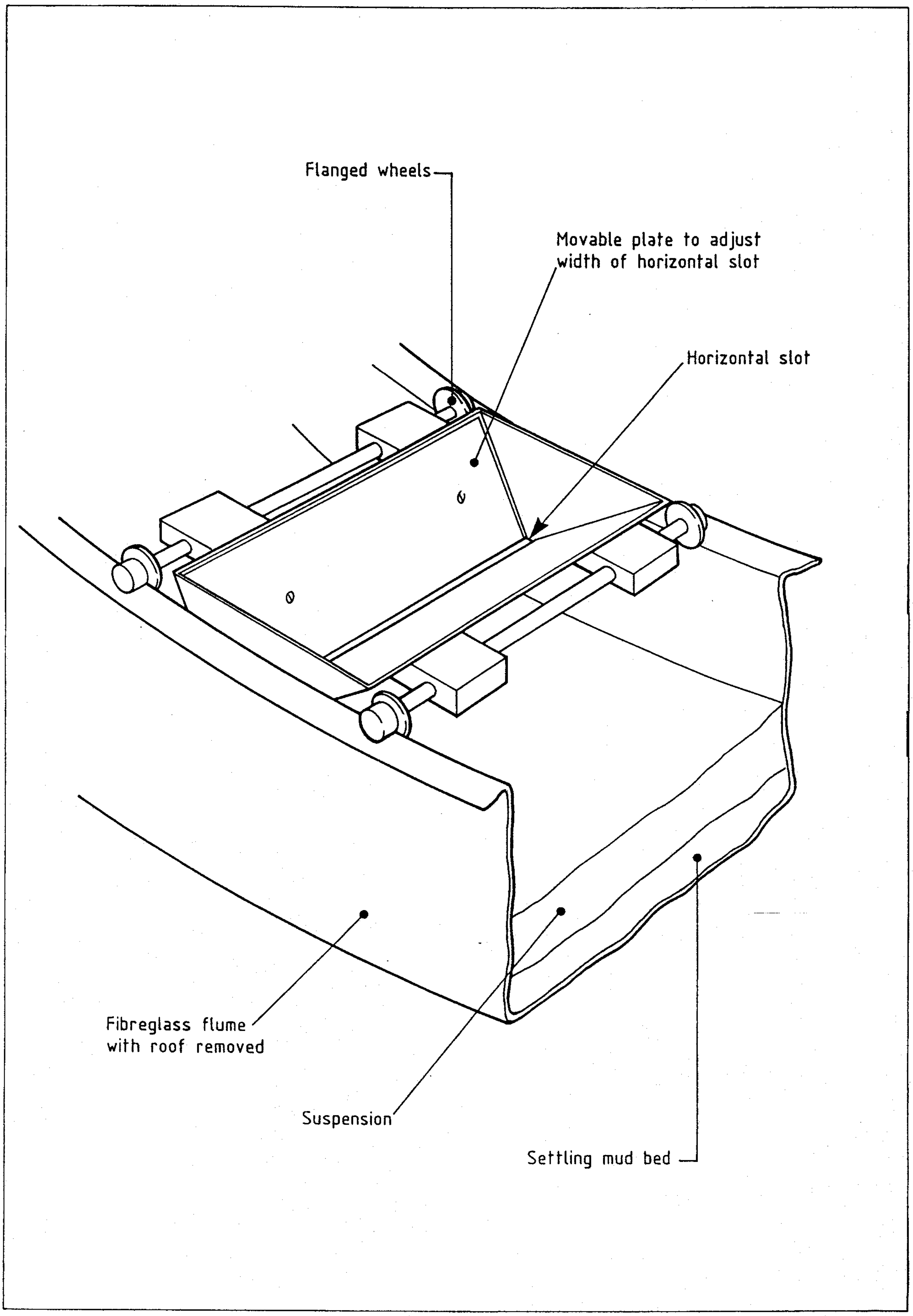

Fig 26 The sand hopper

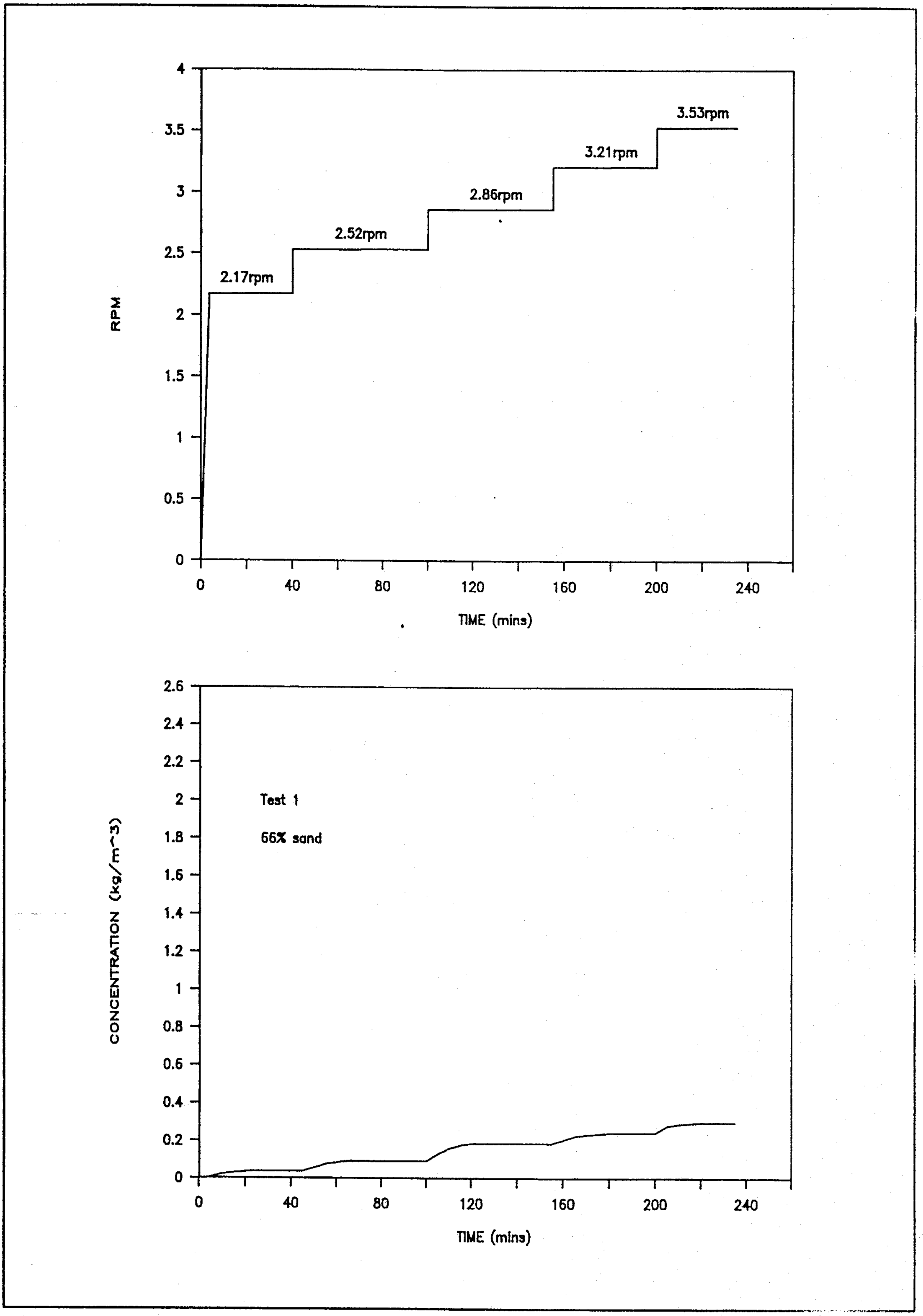

Fig 27 Roof speed and suspended solids concentration, mud/sand Test 1

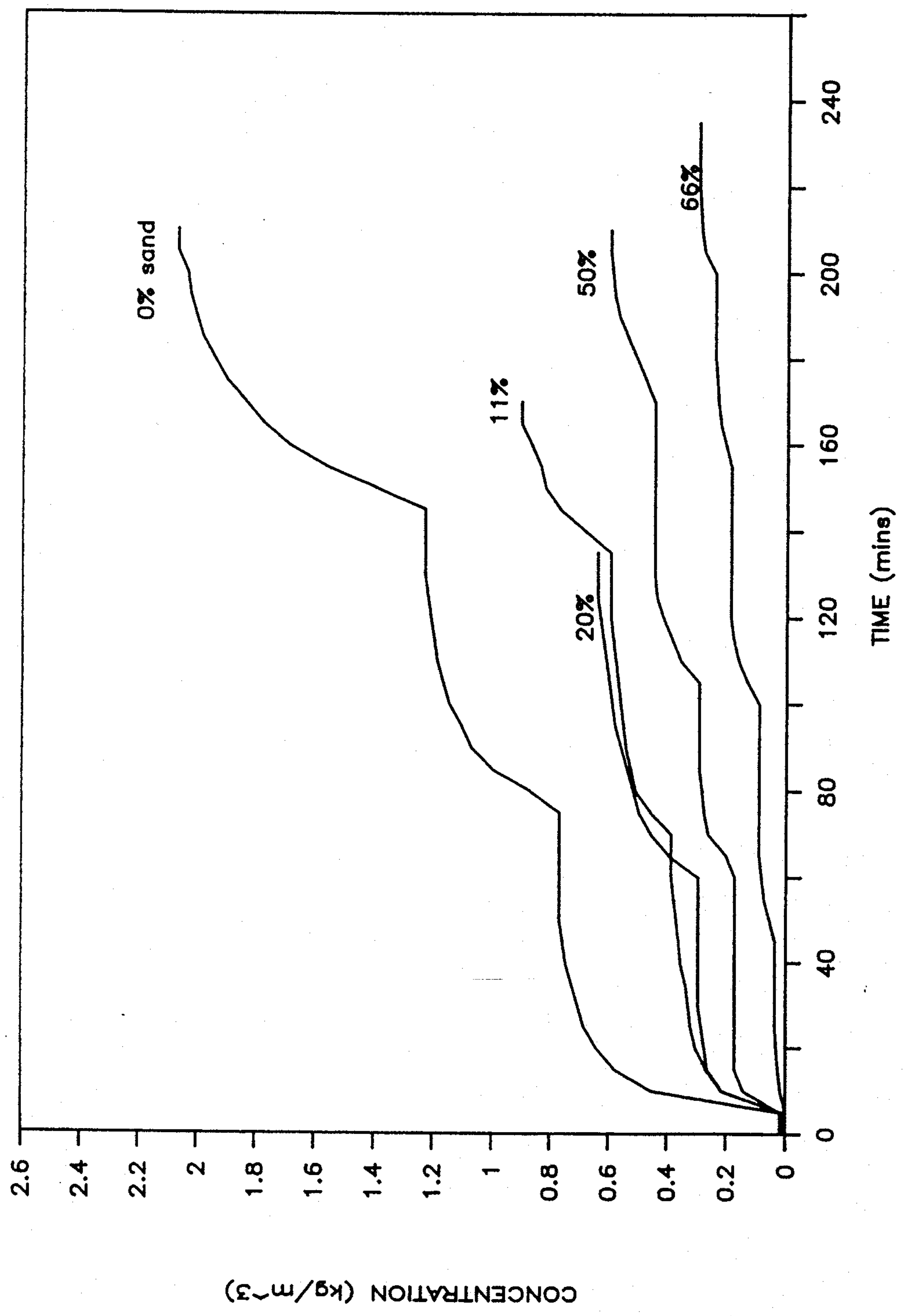

Fig 28 Suspended solids concentration, mud/sand all tests

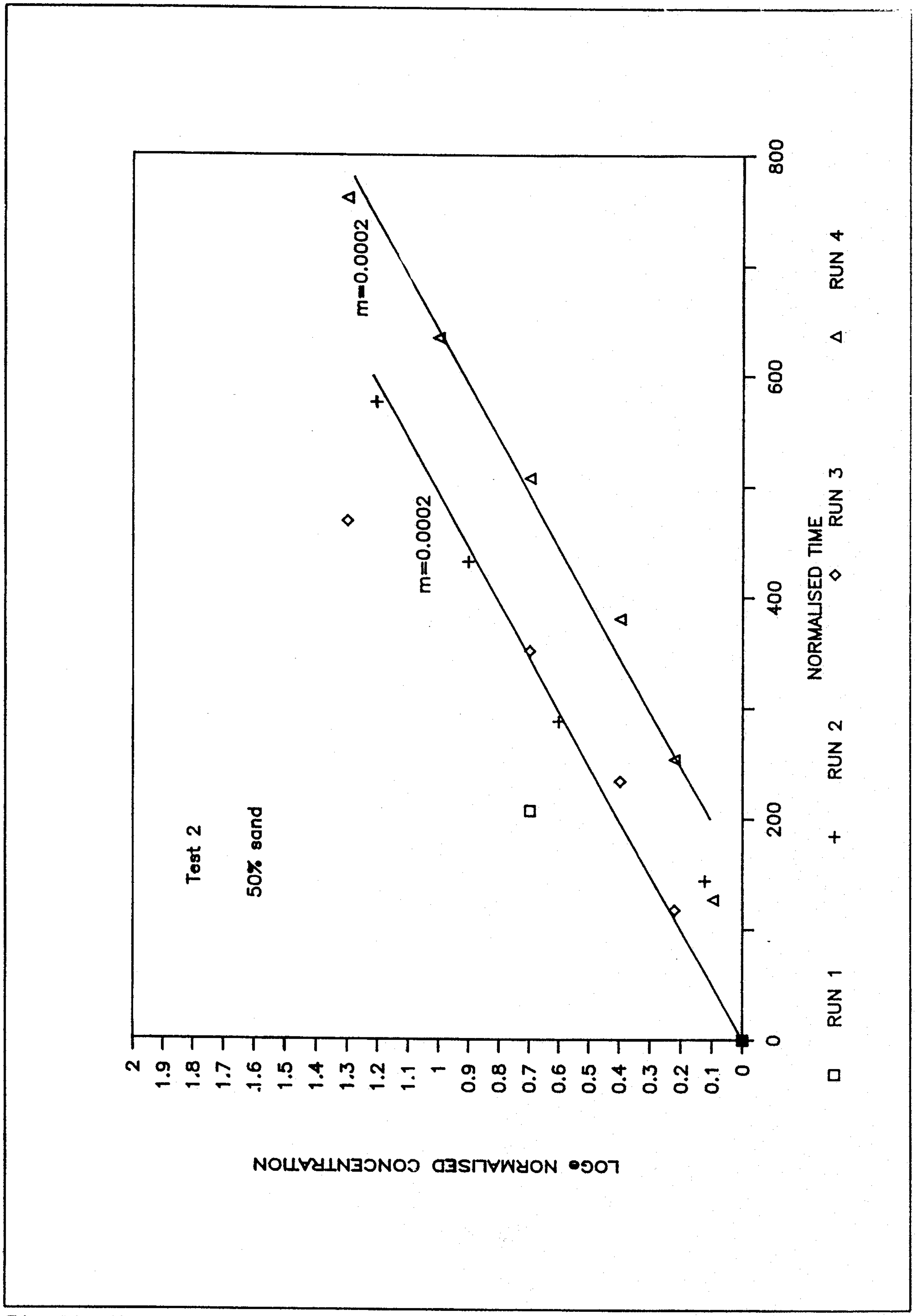

Fig 29 Normalised results of erosion rate, mud/sand Test 2

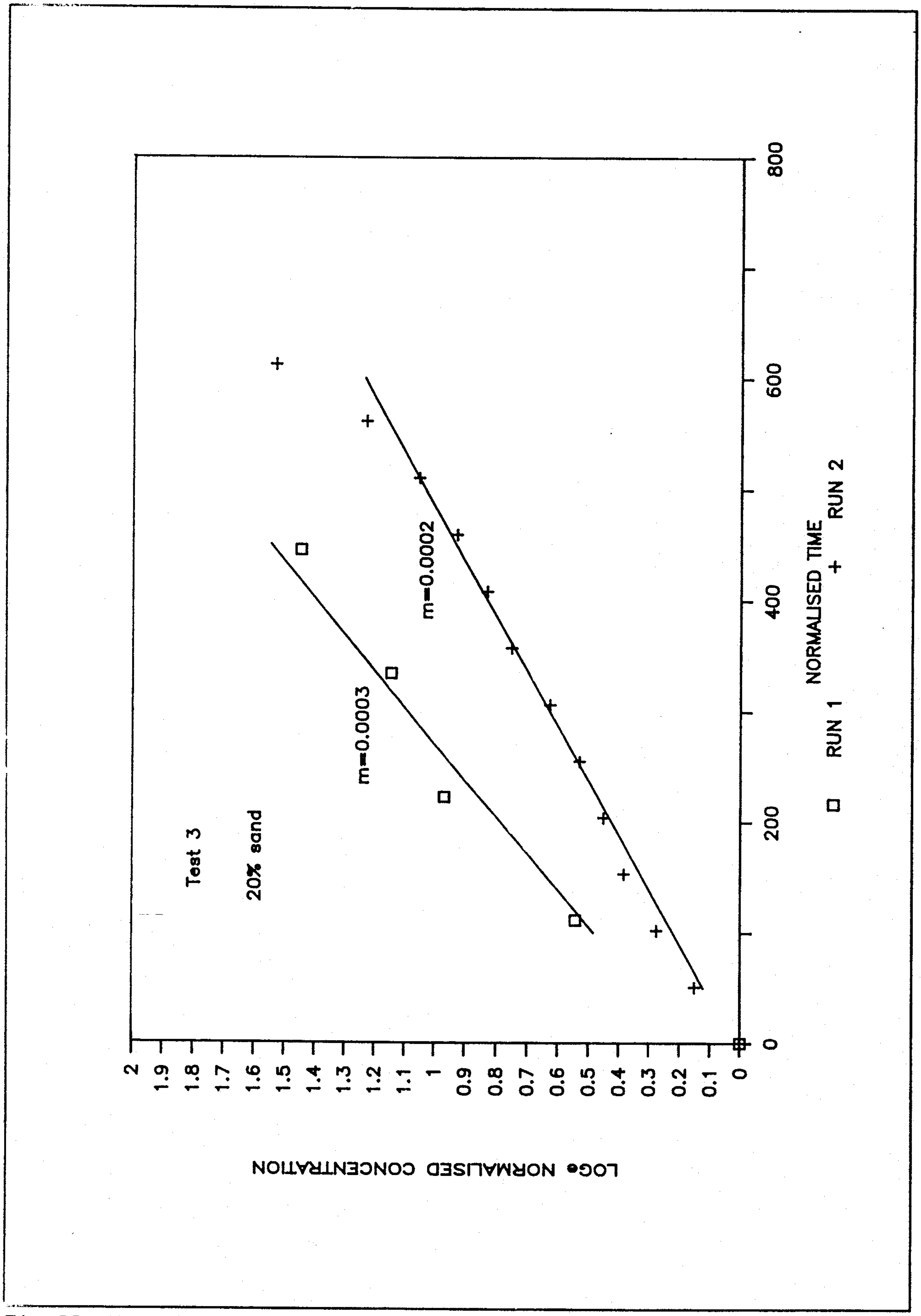

Fig 30 Normalised results of erosion rate, mud/sand Test 3

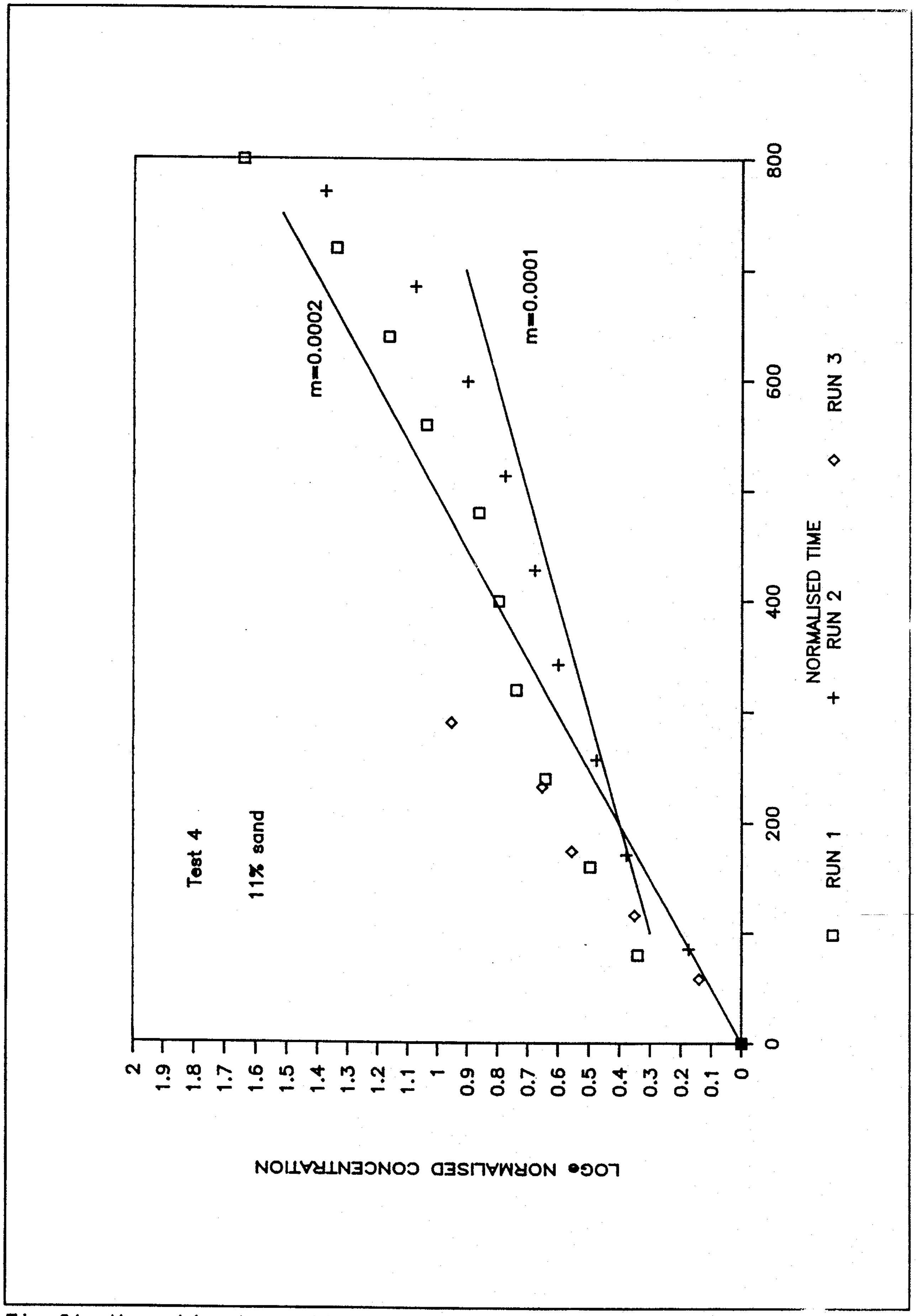

Fig 31 Normalised results of erosion rate, mud/sand Test 4

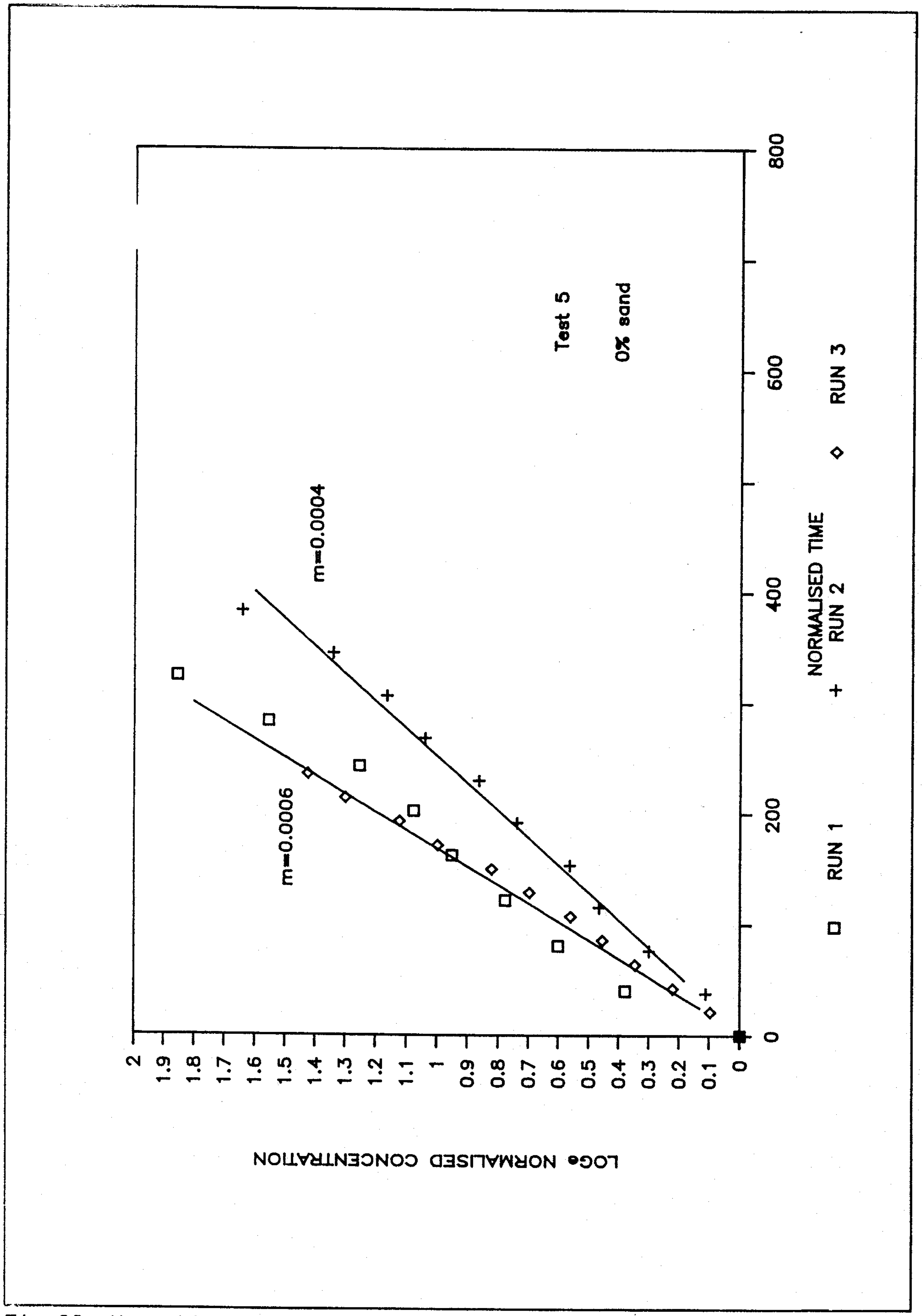

Fig 32 Normalised results of erosion rate, mud/sand Test 5

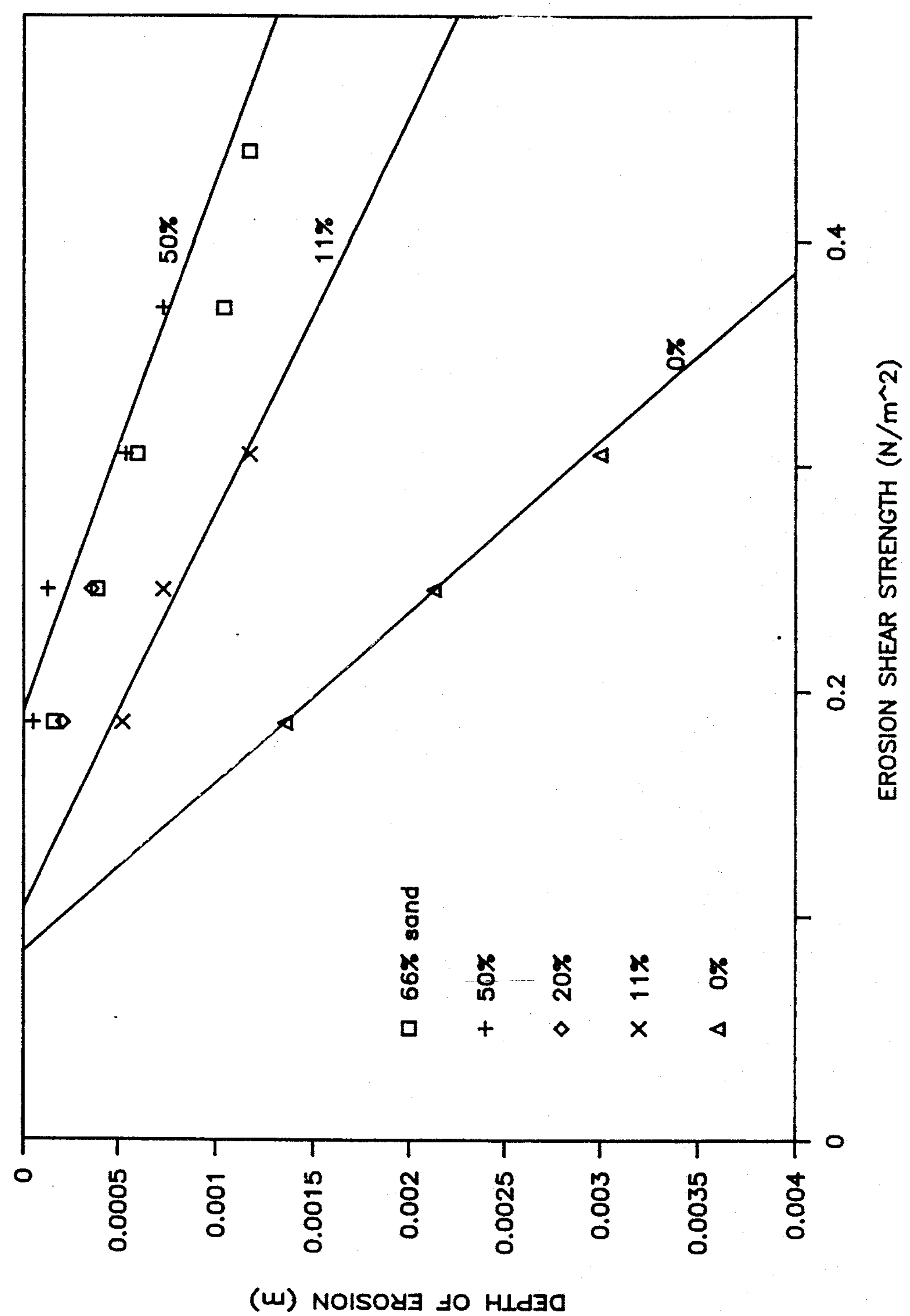

Fig 33 Shear strength against depth of erosion, mud/sand tests

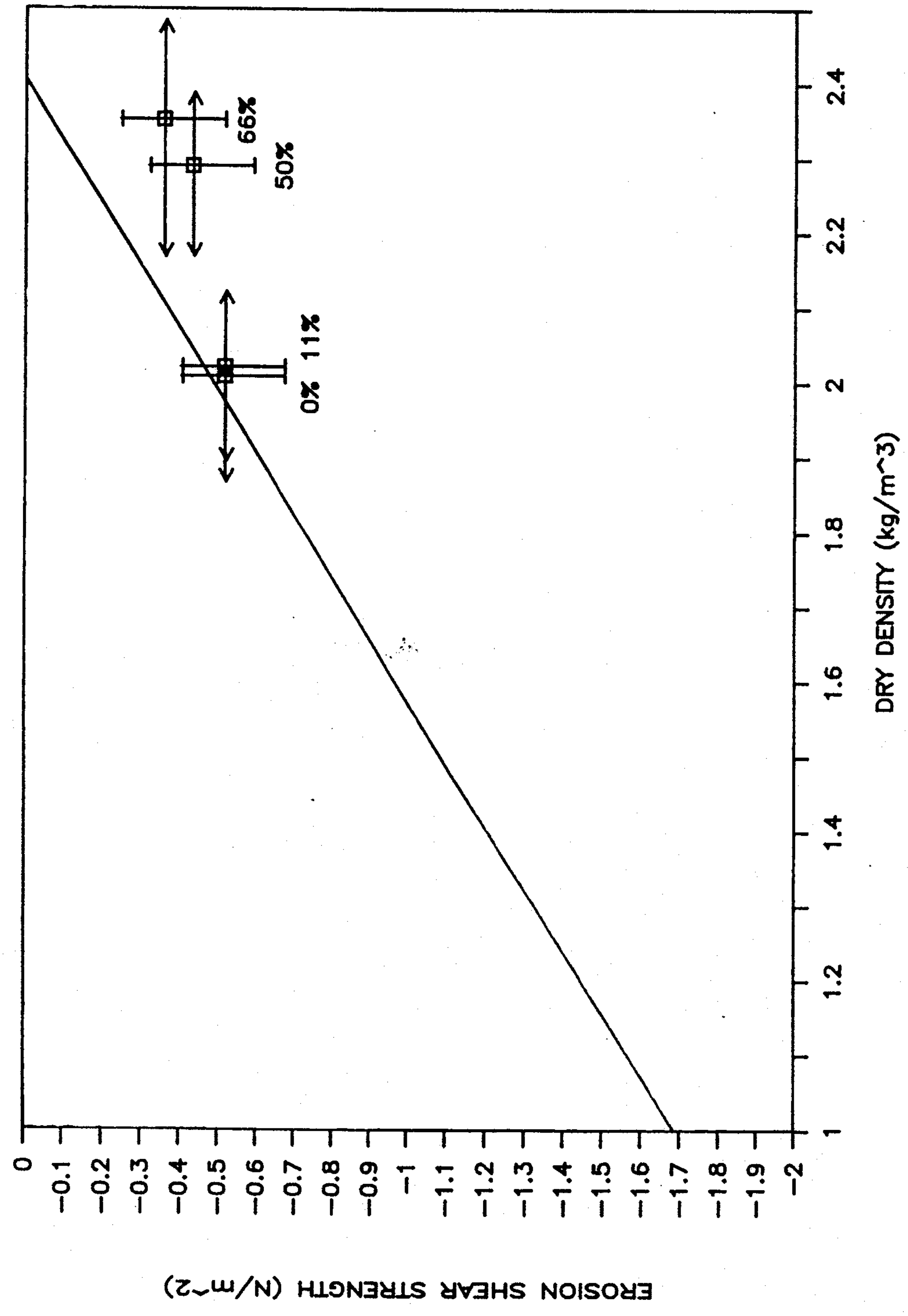

Fig 34 Shear strength with density, mud/sand tests