Hydraulics Research
Wallingford

THE STABILITY OF COHESIVE DREDGED SLOPES UNDER WAVE ACTION

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Report No SR 154
February 1988

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This report describes work funded by the Department of the Environment under Research Contract No PECD 7/6/60 for which the DoE nominated officer was Dr R P Thorogood. The work was also partly funded by Hydraulics Research through its in-house research programme. It is published on behalf of the Department of the Environment, but any opinions expressed in this report are not necessarily those of the funding Department. The work was carried out by Dr E A Delo and Mr A P Diserens in Mr T N Burt's section in the Tidal Engineering Department of Hydraulics Research, Wallingford, under the management of Mr M F C Thorn.

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ABSTRACT

The effect of waves on the stability of dredged slopes is a significant factor which has to be taken into account in the initial design and estimation of maintenance cost of a dredged channel. The effect of waves can be considerable, the passage of a wave will have two effects. Firstly the slope will be subject to fluctuations in hydrostatic pressure and secondly to a shear stress generated by the orbital motions of the water.

The objectives of the study was primarily to develop and evaluate the laboratory equipment for investigating the stability of slopes under waves and also to determine the stability of one specific mud under a range of conditions.

Two series of tests were implemented. The first was to determine the relative stability in terms of time to failure of one specific type of mud with a range of densities and slope angles under a series of different wave conditions. The second series of tests was designed to examine the relationship between maximum applied bed shear stress and rate of entrainment for a horizontal bed of the mud at one particular density. The results of the first series of tests are useful in quantifying the effects of a wave induced shear stress on the stability of a slope of one specific type of mud, and are used to illustrate both the likely general behaviour of muds under the action of waves and the relative sensitivity of the different parameters investigated.

The second series of tests shows that the critical shear stress under waves is of a similar order of magnitude to that under unidirectional currents and that the rate of entrainment for an applied excess shear stress is also a similar order of magnitude to the rate of erosion under unidirectional currents.

The Bingham yield stress was determined for each mud density used and the relationship between the Bingham yield stress and density illustrated. This may be of particular use in future studies in explaining the behaviour of muds of different composition.

Recommendations for further investigations include more detailed tests to determine the stable conditions of dredged slopes under waves with greater accuracy, and comparison of the stability of muds with contrasting composition, to attempt to establish a physical property with which to predict their behaviour under waves of different muds. It is also recommended that the rate of entrainment of mud beds settled from suspension should be determined.

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1. INTRODUCTION

The effect of waves on the stability of dredged slopes is a significant factor which has to be taken into account in the initial design and estimation of the cost of maintenance of a dredged channel.

A review of the methods of analysis and experimental techniques (Delo and Burt 1987) concluded that laboratory scale work need not be viewed as an exact replica of a real prototype but as an attempt to establish laws which apply on laboratory slopes and hence, it is assumed on larger slopes. Methods of analyses include traditional soil mechanics techniques adapted to take into account the effects of moving water, most applicable when the soil fails as a moving block, and the rheological approach which is most applicable when failure is in the form of sediment flow.

The effect of waves can be considerable, the passage of a wave will have two effects, firstly the slope will be subjected to fluctuations in hydrostatic pressure and secondly the slope will be subject to a shear stress generated by the orbital motion of the water. The relative significance of the wave effects is dependent on the depth of water over the slope, the prevailing wave climate and the physical properties of the bed material. Other factors that can effect the stability of a dredged slope are unidirectional currents, earthquakes, sedimentation and biogeochemical effects, the significance of each will be dependent upon a range of environmental parameters.

The objectives of the investigation was to develop and evaluate the laboratory equipment and procedures necessary to implement the investigations and to establish the possibilities and limitations for use in future studies. The objective was to evaluate the stability of slopes for one specific mud. The investigations were split into two series of tests. The first was designed to determine the relative stability in terms of time to failure of slopes of a range of densities and angles under a series of different wave heights. The second series of tests was undertaken to investigate the rate of entrainment into suspension of a horizontal bed under a range of wave conditions.

The Bingham yield stress (together with other rheological properties) was determined for each mud density used. These results were used to illustrate the relationship between Bingham yield stress and density for the mud tested. It is intended to compare the rheological properties with the critical shear stress in future investigations.

2 FLUME APPARATUS

2.1 Description

The experiments were carried out in a rectangular flume 18m long, 0.75m wide and 0.75m deep (see Fig 1). A paddle wave generator at one end of the flume was used to create uniform sinusoidal waves of pre-set height and period. At the opposite end of the flume to the paddle, a spending beach of foam laid at a slope of approximately 45° prevented reflection of the waves.

The flume was fitted with a false floor 6m in length, 5m from the wave generator. A full width trough, 0.7m long and 0.08m deep, was mounted in the final one metre section of the false floor and was hinged enabling mud slopes of between 0° and 15°, perpendicular to the wave front, to be tested. The depth of water in the flume was 0.40m or 0.45m relative to the false floor. A viewing window in the trough section of the flume allowed observation and video-recording of the bed and suspended sediment movement during the tests.

A turbidity sensor was used to measure suspended sediment concentrations at various depths and positions along the flume at time intervals throughout each test. Sampling apparatus was used to retrieve samples for calibration of the turbidity sensor. The turbidity sensor used was an Analite Nephelometer which operated on the principle of backscatter of Infra Red Light. (The degree of backscatter being a function or the reflection coefficient and concentration of suspended sediment).

A small rectangular perspex box 150mm long by 100mm wide with removable end walls was used to take a sample of the bed for density profiling. The box was placed in the trough with its end walls removed prior to filling with the mud bed. At the end of the test the ends were slotted in, the box was removed from the trough and the density profile determined using a Gamma ray transmission density probe.

2.2 Calibration of equipment

The wave amplitude and period at various settings of the wave generator were determined by calibration with a twin wire wave probe. The wave probe gave readings of relative water levels which in conjunction with a chart recorder gave the wave amplitude and period. Both water depths used in the experiments were calibrated for the five settings on the wave generator. (See Table 1).

The Analite Nephelometer turbidity meter was calibrated using water samples from the flume during an erosion test. The concentration of suspended sediment in the sample was determined by a filtration technique. The relationship of the meter reading to concentration (Table 2) was found to be linear over the concentration range of the tests ie 0 to 0.2kg/m^3 (see Fig 2). The equation for the calibration is given by

$$C = 0.377\ R - 0.21 \qquad (1)$$

where C = concentration of suspended sediment (kg/m^3)
R = meter reading

The Gamma ray density probe was calibrated with mud of known bulk density, determined using a pignometer (see Table 3). The count rate to density relationship was also found to be linear over the range of the tests (see Fig 3). The equation for conversion of count rate to density is given by

$$\rho_d = -0.0312\ n + 2065 \qquad (2)$$

where ρ_d = dry density (kg/m^3)
n = counts per minute

2.3 Test procedure

A stock mud from Port Kelang, Malaysia, with a dry density of 720kg/m^3 was used to make up 50 litres of mud of the correct density for each test. The trough was set in the horizontal position and filled with the mud until the mud surface was level with the false floor of the flume. The surface was smoothed and the flume filled with water to the required depth. For each slope stability tests the desired wave settings and slope angle were implemented and the test run until the bed failed, up to a maximum time of three hours. Failure was deemed to have occurred once the channel at the end of the trough was full of mud. This time was recorded for each test.

The erosion rate tests were all undertaken on horizontal beds. The amount of suspended material in the flume was measured at half hourly intervals throughout each test by taking turbidity readings for 3 different depths at 12 positions along the calibrated section of the flume. Three additional readings were also taken at each time interval to determine the amount of suspended sediment between the calibrated section of the flume and the wave generator. Water samples of various concentrations were also taken to calibrate the turbidity meter.

2.4 Analysis

From the calibrated values of wave height and period, and depth of water, the maximum bottom orbital velocity was calculated using first order linear wave theory from the relationship

$$U_m = \frac{\pi H}{T \sinh (2\pi d/L)} \qquad (3)$$

where H = wave height (m)

T = wave period (s)

L = wave length (m)

U_m = maximum bottom orbital velocity (m/s)

d = water depth (m)

The magnitude of the wave length was determined iteratively since

$$\omega^2 = gk \tanh (kd) \qquad (4)$$

where $\omega = 2\pi/T$ (s)

g = acceleration due to gravity (m/s^2)

$k = 2\pi/L$ (m^{-1})

The maximum bed shear stress was calculated from the maximum bottom orbital velocity using the following equation:

$$\tau_m = \rho w \, (2\upsilon\pi/T)^{\frac{1}{2}} U_m \qquad (5)$$

where τ_m = maximum bed shear stress (N/m^2)

ρw = fluid density (kg/m^3)

υ = kinematic viscosity (m/s)

T = wave period (s)

The calculated maximum bottom orbital velocities and bed shear stress at each depth and wave generator setting are shown in Table 1.

The turbidity meter readings were converted into concentration using the calibration equation (1). From each half hourly set of readings the change in the total mass in suspension was calculated by summing the concentration readings over the length of the flume.

The total mass values were normalised to give mass per square metre of bed surface. The rate of entrainment is given by

$$E_r = \frac{dM_s}{dt} \qquad (6)$$

where E_r = rate of entrainment ($kg/m^2/min$)

M_s = mass in suspension per unit area (kg/m^2)

t = time (min)

The relationship between excess shear stress and rate of entrainment for the mud density tested were assessed.

3 FLUME TESTS

3.1 Programme

3.1.1 Stability tests

The first series of experiments was designed to determine the critical conditions of bed slope angle α, maximum bed shear stress τ_b, and bed density ρ_d for failure of a mud slope, and to give an indication of time to failure rate for excess shear stress.

For the first five tests the false floor was 0.1m above the bed of the flume and the depth of water above it was 0.45m. For the subsequent tests the floor was raised to 0.17m and the water depth changed to 0.40m above the new floor level.

Three different wave settings were employed giving a range of bed shear stresses from $0.42N/m^2$ to $0.90N/m^2$; four densities of bed from $352kg/m^3$ to $512kg/m^2$; and a number of bed angles between 0 and 15° (see Table 4).

The tests were undertaken in order of increasing angle, density and wave height; the first test being the lowest angle, density and wave height and the final test being the most dense, largest angle with the highest waves.

Each density and angle combination was tested under all three wave heights, before increasing the angle. Once all tests had been completed on the lowest density the next higher density of bed was used. The same angle and wave conditions were tested and if failure had not occurred within 3 hours for the lower density bed the test was not repeated for the higher density bed.

A stress-relaxation-stress test (Test 28) was designed to find out if there was any recovery in bed shear strength in the hour between two periods of applied bed shear stress. If the bed took longer (in terms of duration of applied bed shear stress) to fail than a bed subjected to the same maximum bed shear stress continuously (Test 10) then this would be an indication of recovery of bed shear strength.

3.1.2 Entrainment

Initially three entrainment tests were planned using low, medium and high wave induced bed shear stresses. These were designed to examine the relationship between rate of entrainment and bed shear stress at a particular bed density. A density of $350kg/m^3$ was chosen since it was noticed during the slope stability tests that there was very little entrainment at any higher densities. After the results of the first three tests had been analysed, the trough was modified to have flexible rubber end walls, as described earlier, and a further two tests were run using mud of similar density.

In test A4 and A5 the removable box was used in conjunction with the gamma ray density probe to determine the vertical bed density profile at the end of the test. In Test A5 a further series of concentration readings were taken in the water column directly above the bed in order to determine the extent and magnitude of the near bed turbid layer, a region of high turbidity in the bottom few millimetres of the water column found to exist in previous studies (Kendrick 1987). This turbid layer is important since in the presence of a current it would mix into higher layers and hence would result in high concentrations throughout the water column.

3.2 Slope stability results

3.2.1 General

The results of the slope stability tests are tabulated in Table 5. The beds with a density of 350kg/m^3 failed in less than one minute at all angles and shear stresses tested. Conversely, beds with a density of 510kg/m^3 were stable for more than 180 minutes under all conditions tested (up to a maximum bed shear stress of 0.90N/m^2 and an angle of 13.5°).

The results of the tests on beds with a density of 400kg/m^3 and 460kg/m^3 were plotted as slope angle against maximum bed shear stress, in Figures 4 and 5, respectively. The data points are labelled with the time to failure if failure occurred between 1 and 180 minutes. Also shown in Figures 4 and 5 are lines depicting a possible trend in the data. These interpretations are tentative and are to be taken as a qualitative indication of the trend.

A graph of slope angle against time to failure was plotted for a density of 400kg/m^3 and a maximum shear stress of 0.43N/m^2 (Fig 6). The relationship between maximum bed shear stress and time was also plotted as an example for a density of 460kg/m^3 and a slope angle of 7.5°. It can be seen from these graphs that both relationships have the form of exponential curves. The highest angles and shear stresses result in the shortest time to failure. The time to failure increases exponentially with decreasing angle and maximum bed shear stress until at some value the time to failure becomes very large. At angles and maximum bed shear stresses below this value the bed is stable.

3.2.2 Bed density

The range of bed densities tested was from 350kg/m^3 to 510kg/m^2. Beds of lower density, as expected, failed at lower angles and bed shear stresses than higher density beds. The beds with density 350kg/m^3 were unstable under all maximum bed shear stresses tested (0.42N/m^2 and above) and all slope angles, even on the horizontal. The beds of density 510kg/m^3, on the other hand, did not fail even under an angle of 13.5° and subjected to the highest maximum bed shear stress (0.89N/m^2).

The results of the tests on the beds with densities in between 400kg/m^3 and 460kg/m^3 are plotted on Figures 4 and 5. The beds with a density of 400kg/m^3 (Fig 4) were found to fail in less than 1 minute for angles of greater than 7.5° and when subjected to a maximum bed shear stress of greater than 0.67N/m^2. They were also found to be stable for over 180 minutes when subjected to an angle below 2.5° and a bed shear stress of less than 0.4N/m^3. The beds with a density of 460kg/m^2 (Fig 5) were stable at higher shear stress/angle combinations. The beds were stable for more than 180 minutes at angles up to 4° when subjected to a maximum bed shear stress of less than 0.52N/m^2.

3.2.3 Slope angle

The slope angle had a marked effect on the stability and rate of failure of mud beds (see Figs 4 and 5). The range of angles tested was from 0 to 13.5°. It was found that the time to failure was decreased by increasing the angle of slope. For example, a bed of density 400kg/m^3 subjected to a maximum bed shear stress of 0.42N/m^2 was stable for more than 180 minutes on the horizontal, whereas it failed in less than 1 minute at a slope angle of 13° (see Fig 4).

3.2.4 Bed shear stress

The maximum bed shear stress is also a major factor affecting the stability and time to failure of mud beds. The range of bed shear stresses tested was from $0.42N/m^2$ to $0.89N/m^2$. A bed of density $460kg/m^3$ with a slope of 7° was found to be stable for over 180 minutes under a shear stress of $0.42N/m^2$ but failed in under 1 minute when subjected to a maximum bed shear stress of $0.89N/m^2$.

A comparison between the effect of increasing the angle and the effect of increasing the peak bed shear stress shows that an increase in maximum bed shear stress of $0.10N/m^2$ has the equivalent effect of increasing the angle by 5° over the range of angles and bed shear stresses tested.

3.2.5 Time

The relationship between slope angle and time failure for one density and shear stress is shown on Figure 6. The relationship between maximum bed shear stress and time for beds of one density and slope angle is shown on Figure 7. As can be seen there is a slope angle and maximum bed shear stress below which the beds are stable.

The stress-relaxation-stress, Test 28, failed after the same cumulative time of maximum bed shear stress as Test 10 (the equivalent continuous test). There was no evidence of recovery of the bed during the period of relaxation.

3.3 Results of entrainment into suspension tests

The test data and results are tabulated in Table 6 for all five entrainment into suspension tests and plotted as total mass in suspension against time in Figures 10 to 13. The erosion rates were found from the gradient of the best fit line through the points calculated by linear regression. Tests A1, A2 and A3 gave rapid increases in concentration for the first half hour. This was caused to a large extent by the effects of the 45° end walls. Once the bed had eroded sufficiently the end effects decreased and the erosion rate became constant with time. In Tests A4 and A5 the bed was retained by vertical flexible rubber end walls which allowed the bed to oscillate freely. These tests gave a constant erosion rate with time from the beginning of the test.

Vertical concentration profiles were measured directly above the bed every 30 minutes throughout Test A5. The results of these readings are presented in Table 7 and plotted as a graph of height above the bed against concentration for all readings together (Figure 14).

The results show a marked increase in concentration in the bottom 40mm in all profiles. This is most noticable in the profile taken at 30 minutes when the concentration increased from 0.06kg/m^3 at 40mm to 0.12kg/m^3 at 5mm above the bed. This region of high concentration may be identified as a near bed turbid layer and has found to exist in previous studies (Kendrick 1987).

Vertical density profiles through the bed were taken, using the removable trough, at the end of Test A4 and A5. The data from these are shown in Table 8. The results showed no significant difference in density between the bottom of the bed and the top, (see Fig 14). From these profiles it may be concluded that there was no significant sorting of the coarser particles over the duration of the tests.

The results of the rate of entrainment tests were plotted as erosion rate against maximum bed shear stress (Fig 15). A trend in the rate of entrainment can be seen from Fig 15. The lower shear stresses resulted in lower erosion rates than the higher shear stresses.

From the work carried out previously on Kelang mud (Hydraulics Research, 1987) the following relationship was derived for the erosion rate in a uni-directional current, ie

$$E = 0.0005\ (\tau - \tau_e) \qquad (7)$$

where E = rate of erosion ($kg/m^2/s$)

τ = bed shear stress (N/m^2)

τ_e = critical bed shear stress (N/m^2)

In Figure 15, the straight line relationship through the data points also relates the entrainment rate to the difference between the applied maximum bed shear stress and a critical shear stress below which no entrainment occurs. The equation of this line is S.I units is given by,

$$E'_r = 0.0003\ (\tau_m - \tau_{mc}) \qquad (8)$$

where E'_r = rate of entrainment ($kg/m^2/s$)

τ_m = maximum bed shear stress (N/m^2)

τ_{mc} = critical maximum bed shear stress (N/m^2)

For the data given in Figure 15, the critical maximum bed shear stress, τ_{mc}, was estimated to be $0.3 N/m^2$.

It would be expected that this critical τ_{mc} is related to the density of the mud and would increase with density. The value of the critical erosion shear stress, τ_e, for Kelang mud of dry density 350kg/m^3 may be estimated by extrapolating the results obtained in the previous study. This is found to give a value close to 1.0N/m^2.

In engineering terms it may be suggested from these few tests that the rates of erosion in uni-directional current and entrainment under waves have similar relationships to excess shear stress (ie equations (7) and (8)). A comparison of τ_e and τ_{mc} for a dry density of 350kg/m^3 indicates a much higher value for the critical stress in uni-directional erosion (ie 1.0N/m^2 compared to 0.3N/m^2).

4 RHEOLOGICAL PROPERTIES

4.1 Introduction

The rheological properties of the mud, for the four densities tested in the flume , were determined by Dr Hardman at the Department of Chemistry, at Reading University (see Hardman, 1988). This section summarises the findings of this investigation.

The resistance to shear of a mud can be defined by its rheological properties rather than correlation with its density. The Bingham yield stress of a mud defines the force necessary to shear it per unit area at the plane of shearing. This property may be more useful than density in predicting the stability of slopes since muds of different compositions will exhibit different resistances to shear at the same density.

The Bingham yield stress is found by subjecting a sample of mud to a shear rate and measuring the shear stress. A plot of stress against shear rate (ideally) gives a straight line relationship for shear rates greater than zero (see Figs 16-19). The shear stress at which the mud just begins to shear is the Bingham yield stress. Often, however, the shear stress to shear rate relationship beyond the Bingham yield stress is non-linear and an estimate of the Bingham yield stress can only be obtained by extrapolation. Thus, to obtain the Bingham yield stress of the mud samples, the shear stress was measured at various shear rates. A graph of shear stress against shear rate was plotted and the Bingham yield stress determined by extrapolation back to zero shear rate.

4.2 Test procedure

Prior to the rheological tests, the particle size distribution of each sample was determined using a Malvern 3600D laser particle size. The size gradings of each sample gave good agreement with each other, having a D_{50} of approximately 8μm, a D_{90} of approximately 40μm and a D_{10} of approximately 2.8μm. These figures compared well with Hydraulic Research's gravimetric determination which gave a D_{50} of 10μm and a D_{90} of 80μm (Hydraulics Research, 1987).

A Bohlin rheometer fitted with a C25 concentric cylinder (selected so that the spacing between the concentric cylinders is large compared to the size of the particles). A 96.2gcm torque element and 'viscosity' software was used for the experimental work and data analysis.

Each sample of mud was shaken to produce a homogenous suspension and a syringe used to transfer a small quantity to the measuring cup of the rheometer. The sample was sheared (1.861×10^{-3} to $14.65\ s^{-1}$) and the shear stress measured. A hysteresis test was also carried out for each sample, from low to high to low shear rate. All experiments were carried out at 25.0°C and a fresh sample of mud (ie unsheared) used for each run.

4.3 Results

The results of the shear tests were plotted as stress against shear rate. The Bingham yield stress found by extrapolating the line of best fit by eye to zero shear rate. (Figs 16 to 19 show the results of the hysteresis tests). The results of both series of tests is given in Table 8 and plotted as Bingham yield stress against density (Fig 20).

The graph shows increasing Bingham yield stress with increasing density. It is also evident that there is a far greater increase in Bingham yield stress at the higher densities than the lower densities.

4.4 Discussion

The hysteresis tests exhibits the effect of 'shear thinning' a decrease in viscosity with increasing shear rate. This may be explained by the fact that the majority of the particles are plate-like clay particles. When shearing occurs the particles become aligned in the direction of shear.

After shearing the samples, the particles remain aligned for some time. This is illustrated by the fact that the stress/strain hysteresis curve for decreasing shear rate is lower than that for the increasing shear rate (see Figs 16-19).

The Bingham yield stress values for these mud samples was of the same order as that found for Antwerp sediments (Verreet et al, 1986). Antwerp mud with a density of approximately 275kg/m^3 had a Bingham yield stress of $10N/m^2$ whereas Port Kelang mud with a density of $360kg/m^3$ had a Bingham yield stress of $20N/m^2$.

5 FIELD APPLICATION

5.1 Limitations of results

Before discussing the practical significance of the results obtained in the flume experiments it is necessary to identify some of the possible limitations of the methods adopted. Although, the results are most useful in quantifying the effects of a wave induced bed shear stress on the stability of a slope, it has to be recognised that, at present, the results are specific to one type of mud. As such, the results do not necessarily indicate the behaviour of any other type of mud. The trends that the results show, however, may be used to illustrate the likely general behaviour of muds under the action of waves and the relative sensitivity of different parameters in respect to the stability of underwater cohesive slopes.

The nature of the restraint to the mud bed during a test provided either by the sloping sides to the trough or later by the flexible rubber retaining strips is considered to be less than ideal. In reality, a mud slope could extend for many tens of metres and as such any short length of slope is constrained by similar mud to itself at either end. To some degree the failure of a particular mud bed was dependent on its end conditions, ie, trough slope or the flexibility of the rubber strip.

Furtheremore, it was inevitable that the definition of failure was to some degree subjective, except in tests where failure occurred either very quickly or not at all. It was also initially hoped that some measurement of the bulk net movement of mud down the slope could be made, but, due to the difficulties of providing satisfactory end conditions such measurement was in practice not possible.

5.2 Procedure

To assess the likely effect of waves on a dredged slope it would be necessary to determine the variation in density with depth through the slope and to obtain a sample of the mud for laboratory testing. This requirement would be over and above the useful geotechnical parameters such as undrained shear strength and poor pressure which would be essential for a static analysis of the stability of the slope.

The purpose of obtaining a sample of the mud would be to enable some tests in a wave flume to be undertaken to determine the sort of empirical relationships given in Figures 4 and 5. Until the controlling parameter for the behaviour of a mud slope under the action of waves can be clearly identified, be it density or a rheological parameter, laboratory testing would be essential.

In addition to the mud properties it would also be necessary to have a knowledge of the likely significant wave heights and periods in the region where the dredged slope is sited. These coupled with water depths would enable the maximum bed shear stress to be calculated on a probabilistic basis. In addition, it would be important to know the likely range of tidal currents, and hence, current induced bed shear stresses.

The approach recommended in assessing the impact of waves on a dredged slope may be re-stated as field survey, laboratory testing and desk calculation. With respect to the calculation aspects this could take the form of an initial static analysis based on classical solutions (see Delo and Burt, 1987 for a review) followed by an appraisal of different wave conditions on the likely degradation of the dredged slope. In most field situations the density of the exposed surface of the dredged slope would increase down the slope. The effect of a particular wave induced maximum bed shear stress would therefore become progressively less severe down the slope because the density would be increasing. It could be quite feasible for a particular slope configuration and density variation with depth, that the surface fails rapidly at the top of the slope for a given applied maximum bed shear stress but is stable at a certain distance down the slope.

Applying general quantitative values to the effect of waves on a dredged slope in a particular mud is not possible 'due to the widely differing behaviour of mud and the varying wave conditions at locations throughout this country and the world. However, from the point of view of interpreting the significance of the findings for the Kelang mud it may be useful to quote some examples. Let us assume that a 4m deep slope is to be dredged in Kelang mud and that the dry density varies from 300kg/m^3 at the surface to 500kg/m^3 at a depth of 4m. From a classical analysis of the stability of the underconsolidated submerged slope in still water it is assumed that the stable angle is approximately 7 degrees. If the wave conditions in the area suggest that the maximum bed shear stress for say, a return period of 1 year (ignoring current induced shear stress) is approximately 0.5N/m^2 then what effect will this have on the design of the dredged slope?

From the results of laboratory tests on mud densities of 350, 400, 460 and 510kg/m^3 it was found (see section 3.2) that beds with the lowest density failed at any slope angle for maximum bed shear stresses greater than 0.42N/m^2 while those with the highest did not fail even at an angle of 15 degrees and a shear stress of 0.90N/m^2. The two intermediate densities of bed indicated that at 400kg/m^3 and a shear stress 0.5N/m^2 (Fig 4) a slope angle of one or two degrees may be stable in the long run, whereas, at a density of 460kg/m^3 (Fig 5) a slope of between 2 to 5 degrees may withstand a maximum bed shear stress of 0.5N/m^2. Therefore, it is apparent that a considerable part of the slope would probably fail if a dredged slope of 7 degrees was subject to a shear stress of 0.5N/m^2. A possible outline of the degraded slope after experiencing the described wave conditions could be obtained from the equilibrium slope angles quoted above and their respective depth from the surface of the bed. If this outcome was unacceptable then a flatter slope would need to be considered and the likely effect of waves again assessed.

6.1 Conclusions

1. The results of the tests are specific to one type of mud and as such do not necessarily indicate the behaviour of any other mud, however the trends that the results show may be used to illustrate the likely effects of different parameters in respect to stability of underwater slopes under waves.

2. Until the controlling parameter for the behaviour of mud slopes has been clearly identified, be it density or a rheological parameter, laboratory testing is essential in predicting the stability of a mud slope.

3. The stability of a dredged slope could be assessed by, first determining the usual geotechnical parameters of the mud and implementing conventional static analysis, followed by an appraisal of the likely effect on the slope of the prevailing local wave climate and water depths based on a series of laboratory flume tests.

4. The critical shear stress under waves was found to be of a similar order of magnitude to that under uni-directional currents and the rate of erosion to excess shear stress relationship was also found to be of the same order as that for uni-directional currents.

6.2 Recommendations

1. Future tests should include a preliminary investigation to determine the 180 min to failure conditions at each density, followed by more detailed tests to determine accurately the conditions leading to failure after 180 mins.

2. An investigation of the stability of muds with contrasting composition should be undertaken to try and establish a physical property with which to predict the behaviour under waves of muds of different compositions.

3. A field investigation to compare stability of slopes in field conditions and those predicted from laboratory experiments.

4. An investigation of the rate of entrainment for beds settled from suspension for a closer comparison with uni-directional current erosion tests.

5. Investigation of the rates of entrainment for beds subjected to both waves and currents simultaneously (these can be either placed or settled beds) to determine the combined effect on the rate of erosion.

6. Addaption of cohesive sediment transport models to include the effects of entrainment by waves.

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TABLES.

TABLE 1 WAVE CALIBRATION AND BED SHEAR STRESS DATA

Wave Setting	Water Depth (m)	Wave Height (m)	Wave Period (s)	Wavelength (m)	Um (m/s)	Tm (N/m^2)
0.50	0.40	0.053	1.33	2.24	0.197	0.43
1.00	0.40	0.069	1.33	2.24	0.240	0.52
1.50	0.40	0.089	1.33	2.24	0.308	0.67
2.00	0.40	0.101	1.33	2.24	0.350	0.76
2.50	0.40	0.118	1.33	2.24	0.409	0.89
0.50	0.45	0.062	1.33	2.32	0.191	0.42
1.00	0.45	0.072	1.33	2.32	0.221	0.48
1.50	0.45	0.096	1.33	2.32	0.296	0.65
2.00	0.45	0.107	1.33	2.32	0.326	0.71
2.50	0.45	0.124	1.33	2.32	0.379	0.83

TABLE 2 TURBIDITY METER CALIBRATION

Concentration (kg/m^3)	Meter Reading
0.000	0.20
0.010	0.23
0.020	0.25
0.050	0.34
0.100	0.50
0.200	0.74
0.300	1.01

TABLE 3 DENSITY METER CALIBRATION

Density (kg/m^3)	Meter Reading
0	66380
240	58506
416	52509
512	50250

TABLE 4 RESULTS OF SLOPE STABILITY TESTS

TEST No.	MAX SHEAR (N/m^2)	DRY DENSITY (kg/m^3)	SLOPE ANGLE (degrees)	TIME OF FAILURE (mins)
1	0.670	352	0	<1
2	0.420	352	5	<1
3	0.420	352	1	<1
4	0.420	352	0	<1
5	0.830	352	0	<1
6	0.890	416	0	<1
7	0.670	416	7.5	<1
8	0.670	416	1	15
9	0.670	416	2.5	10
10	0.670	416	0	120
11	0.430	416	2.5	>180
12	0.430	416	13.5	30
13	0.430	416	0	>180
14	0.430	416	7.5	60
15	0.890	464	0	<1
16	0.760	464	2.5	40
17	0.760	464	7.5	3
18	0.760	464	0	60
19	0.670	464	0	120
20	0.520	464	7.5	30
21	0.520	464	0	>180
22	0.520	464	2.5	>180
23	0.890	512	5	>180
24	0.890	512	15	>180
25	0.890	512	9	>180
26	0.890	512	0	>180
27	0.430	512	0	>180
28	0.670	416	0	120

TABLE 5 RESULTS OF RATE OF ENTRAINMENT TESTS

TEST NO : A1
BED DENSITY : 350 kg/m^3
BED SHEAR STRESS: 0.43 N/m^2
EROSION RATE : 0.35 g/min

TIME (mins)	TOTAL EROSION (kg/m^2)
0	0.000
15	0.061
30	0.060
60	0.083
120	0.091
150	0.123
180	0.079
210	0.122
240	0.161

TEST NO : A2
BED DENSITY : 350 kg/m^3
BED SHEAR STRESS: 0.65 N/m^2
EROSION RATE : 5.79 g/min

TIME (mins)	TOTAL EROSION (kg/m^2)
0.0	0.000
15.0	0.200
30.0	0.706
60.0	1.030
90.0	1.362
120.0	1.487
150.0	1.567
180.0	1.460
210.0	1.973

TEST NO : A3
BED DENSITY : 350 kg/m^3
BED SHEAR STRESS: 0.83 N/m^2
EROSION RATE : 7.24 g/min

TIME (mins)	TOTAL EROSION (kg/m^2)
0	0.000
30	1.535
60	2.318
90	2.394
120	2.469
150	2.864
180	3.145
210	3.394
240	3.452

TEST NO : A4
BED DENSITY : 350 kg/m^3
BED SHEAR STRESS: 0.67 N/m^2
EROSION RATE : 7.45 g/min

TIME (mins)	TOTAL EROSION (kg/m^2)
0	0.000
30	0.249
60	0.389
90	0.501
120	0.884
150	1.236

TEST NO : A5
BED DENSITY : 350 kg/m^3
BED SHEAR STRESS: 0.89 N/m^2
EROSION RATE : 7.45 g/min

TIME (mins)	TOTAL EROSION (kg/m^2)
0	0.000
30	0.067
60	0.194
90	0.476
120	0.614
150	0.732
180	0.889

TABLE 6 TEST A5 VERTICAL CONCENTRATION PROFILES

HEIGHT ABOVE BED (mm)	30 mins (kg/m^3)	60 mins (kg/m^3)	90 mins (kg/m^3)	120 mins (kg/m^3)	150 mins (kg/m^3)	180 mins (kg/m^3)
25	0.128	0.053	0.109	0.147	0.177	0.143
50	0.075	0.057	0.102	0.147	0.136	0.136
75	0.057	0.045	0.094	0.147	0.125	0.125
100	0.060	0.045	0.098	0.143	0.109	0.113
150	0.057	0.049	0.087	0.125	0.109	0.109
200	0.057	0.045	0.089	0.121	0.109	0.109
250	0.057	0.034	0.094	0.117	0.106	0.109
300	0.057	0.034	0.091	0.117	0.106	0.109
350	0.053	0.034	0.087	0.113	0.102	0.106

TABLE 7 VERTICAL DENSITY PROFILES TEST A4 AND A5

DEPTH BELOW SURFACE (mm)	TEST A4 METER READING	TEST A4 DENSITY (kg/m^3)	TEST A5 METER READING	TEST A5 DENSITY (kg/m^3)
2.5	27105	376	26985	384
5.0	26831	393	27005	383
10.0	26915	388	27098	377
15.0	26829	394	26915	388
20.0	26700	402	26987	384
25.0	26935	387	27135	374
30.0	26715	401	26866	391
35.0	26915	388	26898	389
40.0	26831	393	27137	374
45.0	26825	394	26988	384
50.0	27108	376	27063	379
55.0	26945	386	26981	384
55.0	26992	383	27125	375
55.0	26921	388	27136	374

TABLE 8 RESULTS OF RHEOLOGICAL TESTS

DRY DENSITY (kg/m^3)	BINGHAM YIELD STRESS RUN 1 (N/m^2)	RUN 2 (N/m^2)
352	19 (+9~,-10)	18 (+4,-1)
416	37 (+3,-2)	37 (+3,-3)
464	67 (+6,-3)	55 (+3,-4)
512	137 (+8,-8)	129 (+5,-3)

The Figures in brackets are estimates of the error in measuring the Bingham yield stress from the graphs.

~ Possibly the result of a spurious point.

FIGURES.

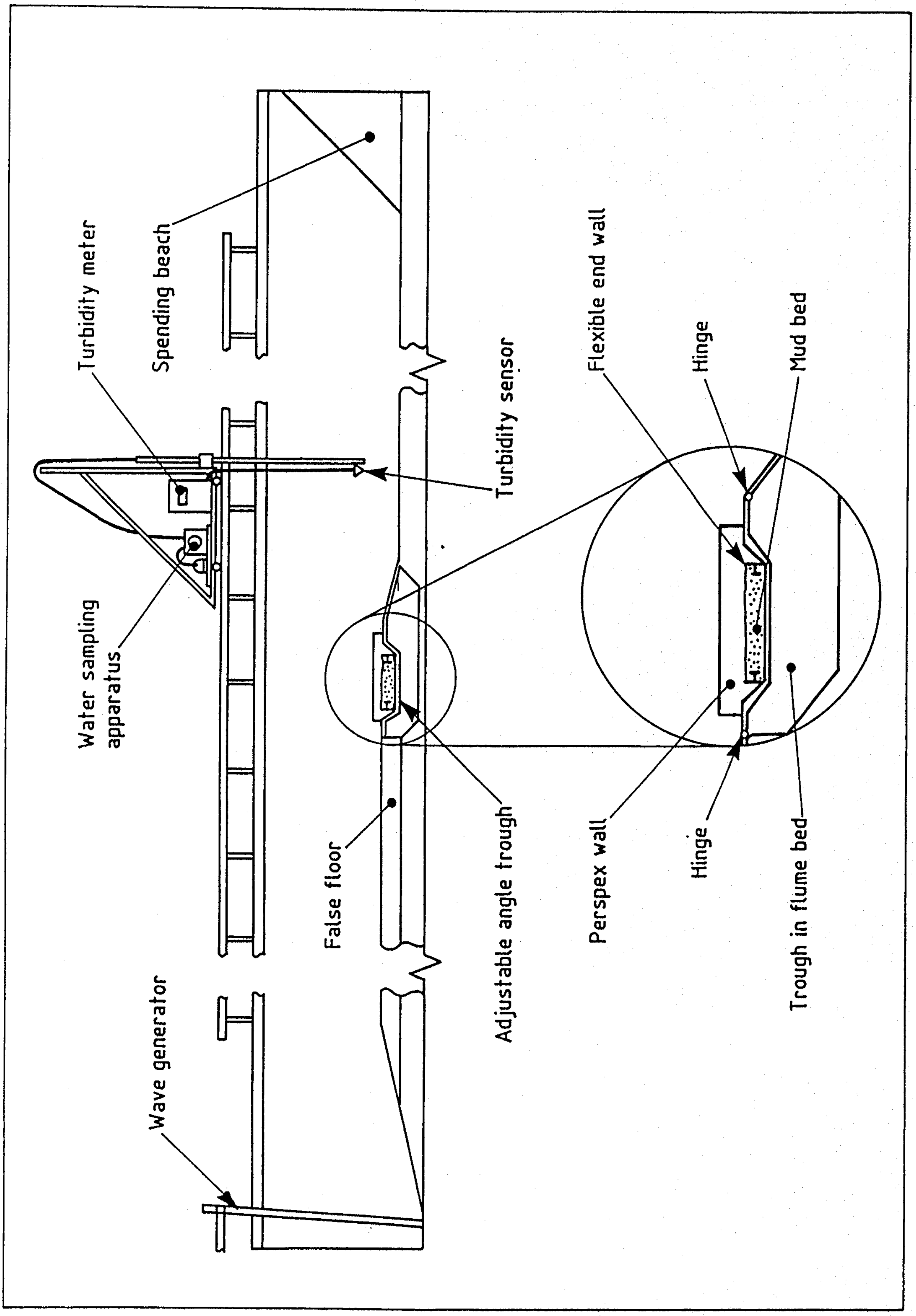

Fig 1 Flume apparatus

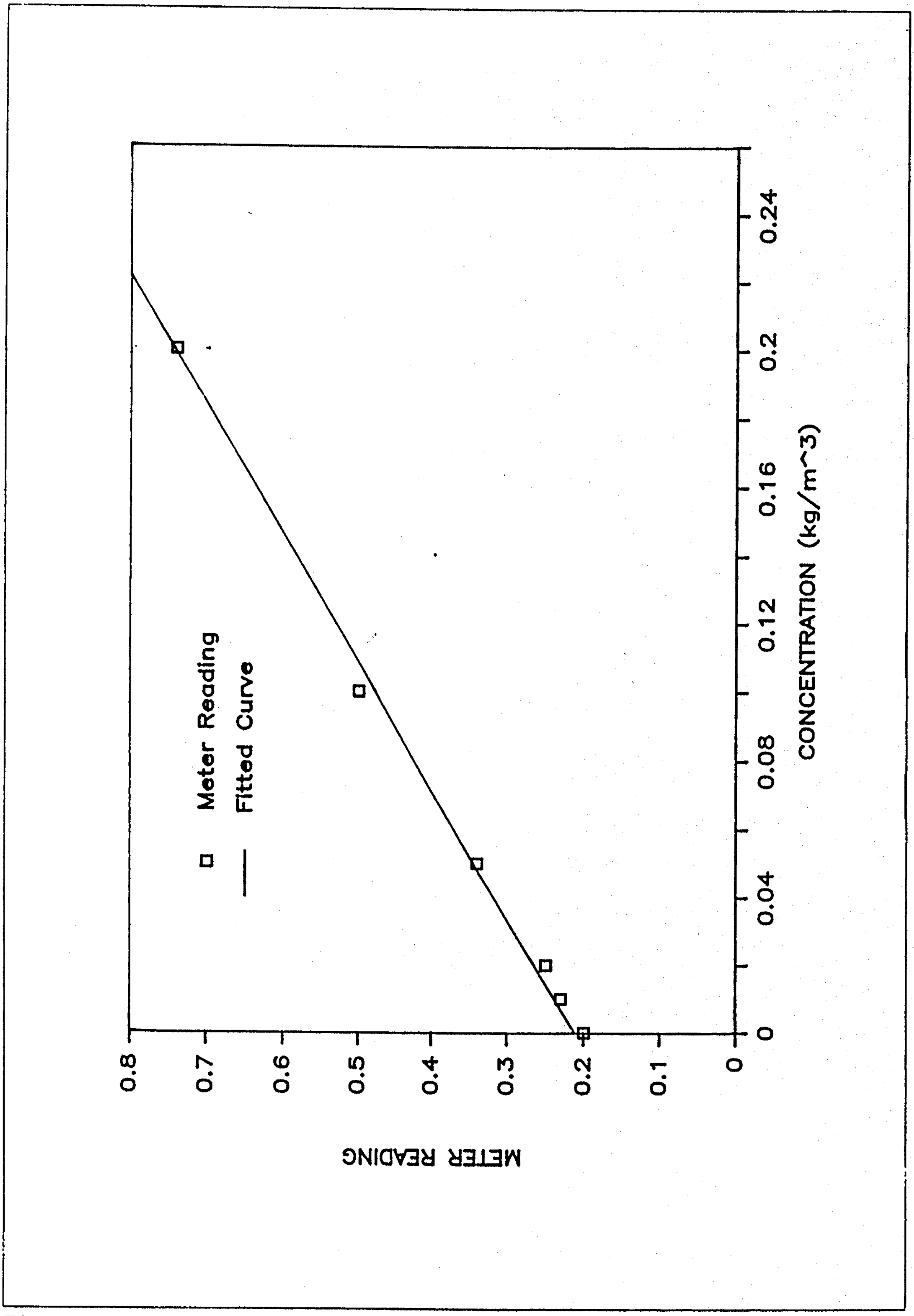

Fig 2 Calibration of Nephelometer

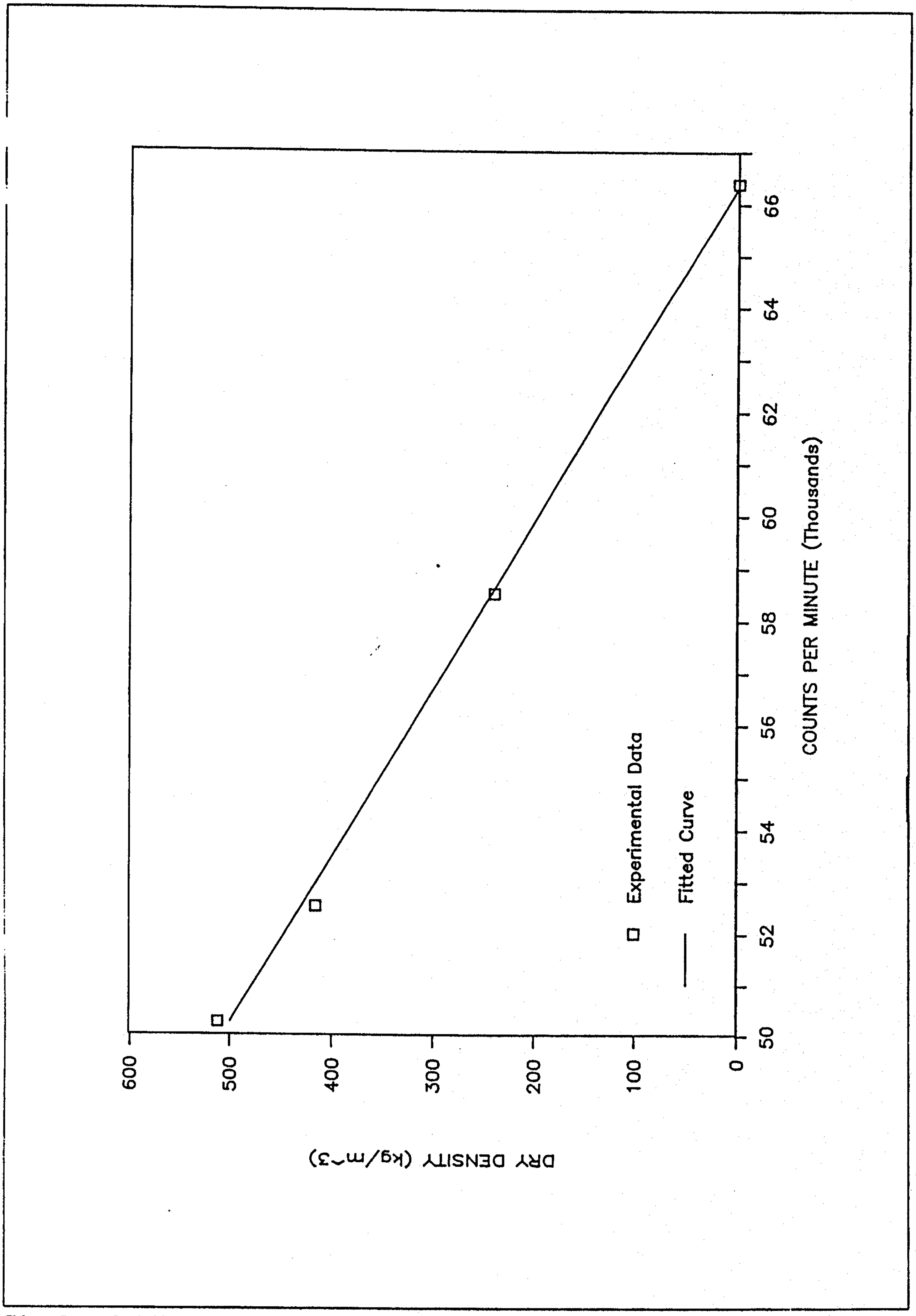

Fig 3 Calibration of density probe

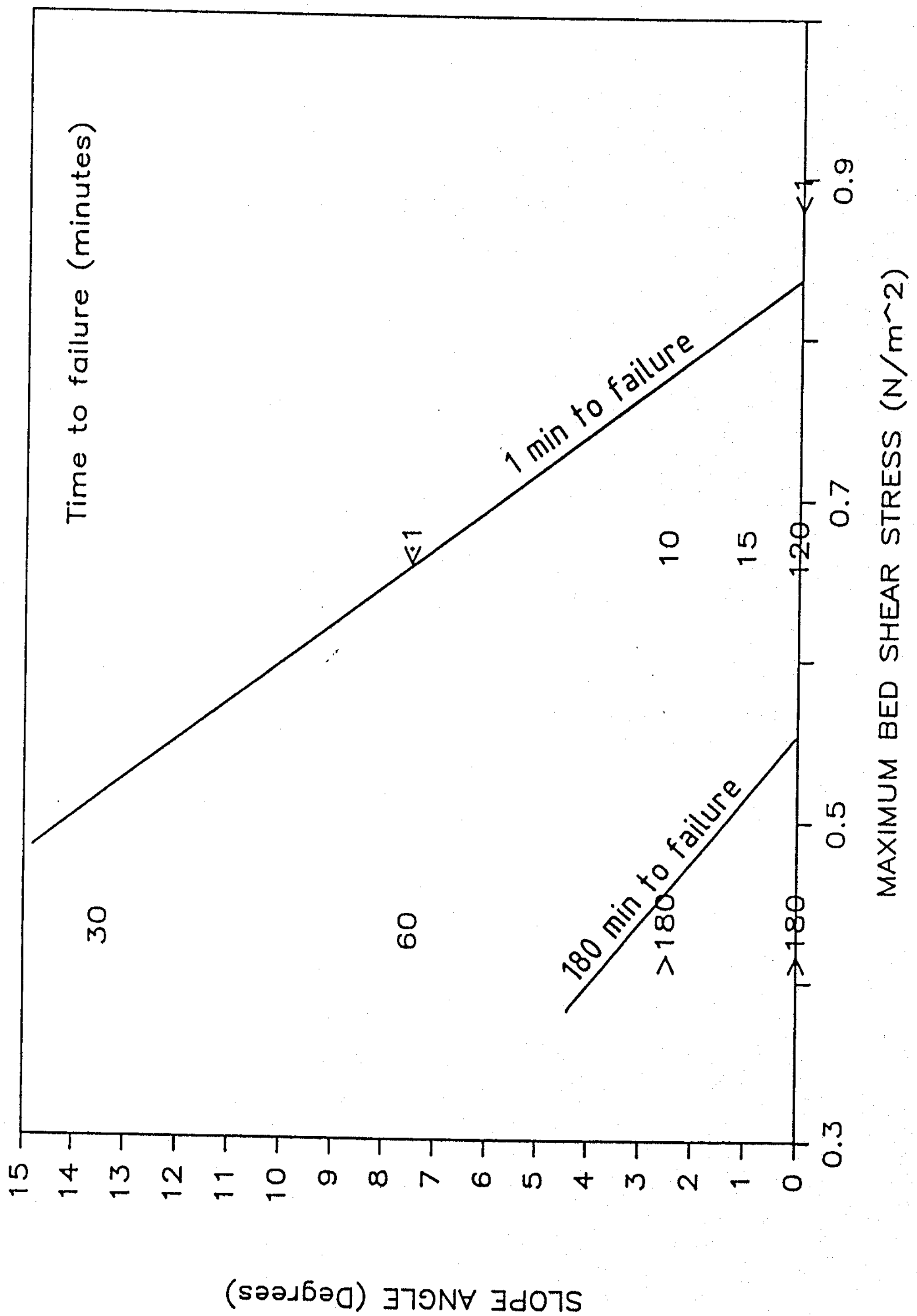

Fig 4   Bed density 400kg/m↑3 slope tests

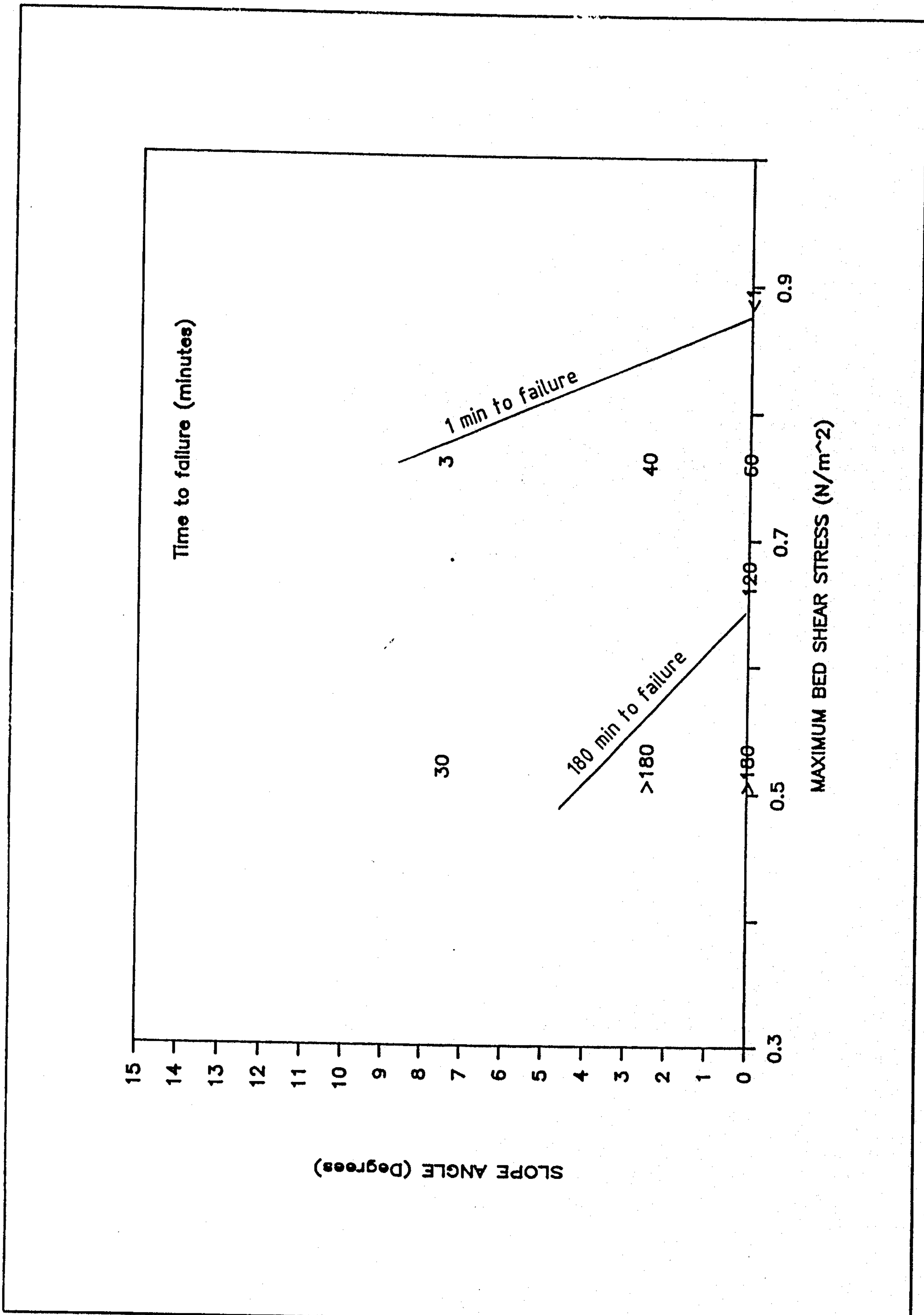

Fig 5 Bed density 460kg/m↑3 slope tests

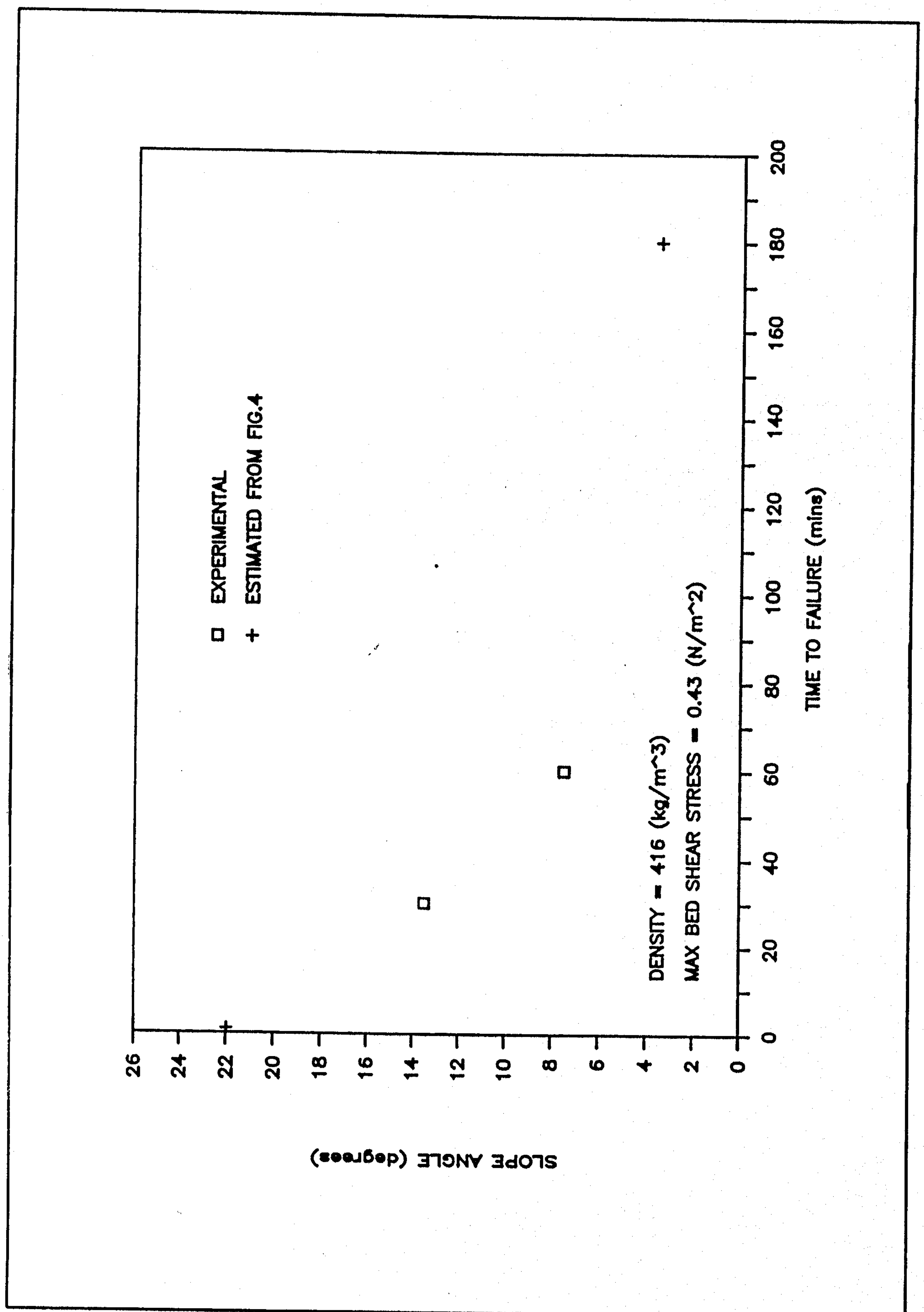

Fig 6 Angle against time to failure

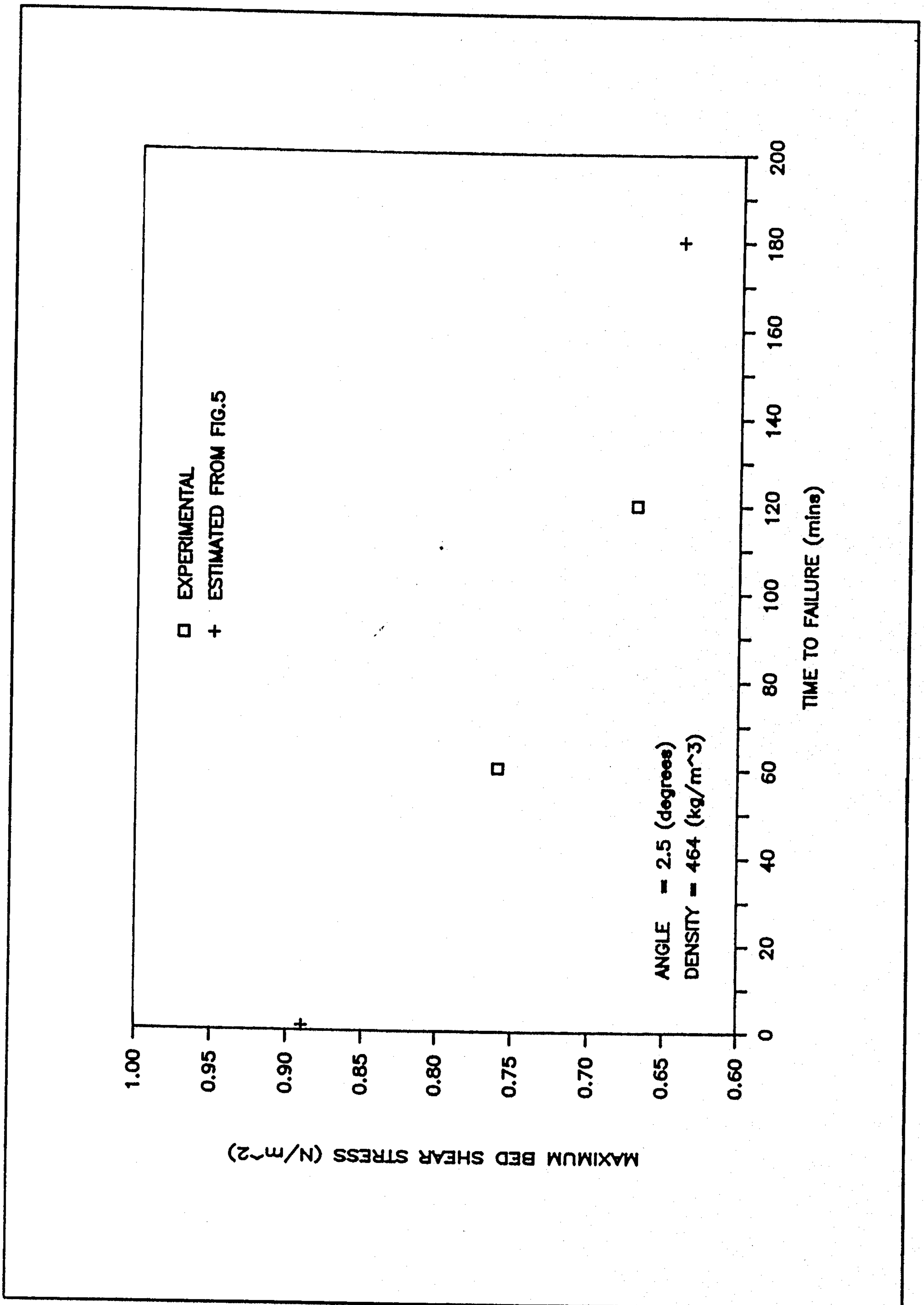

Fig 7 Maximum bed shear stress against time to failure

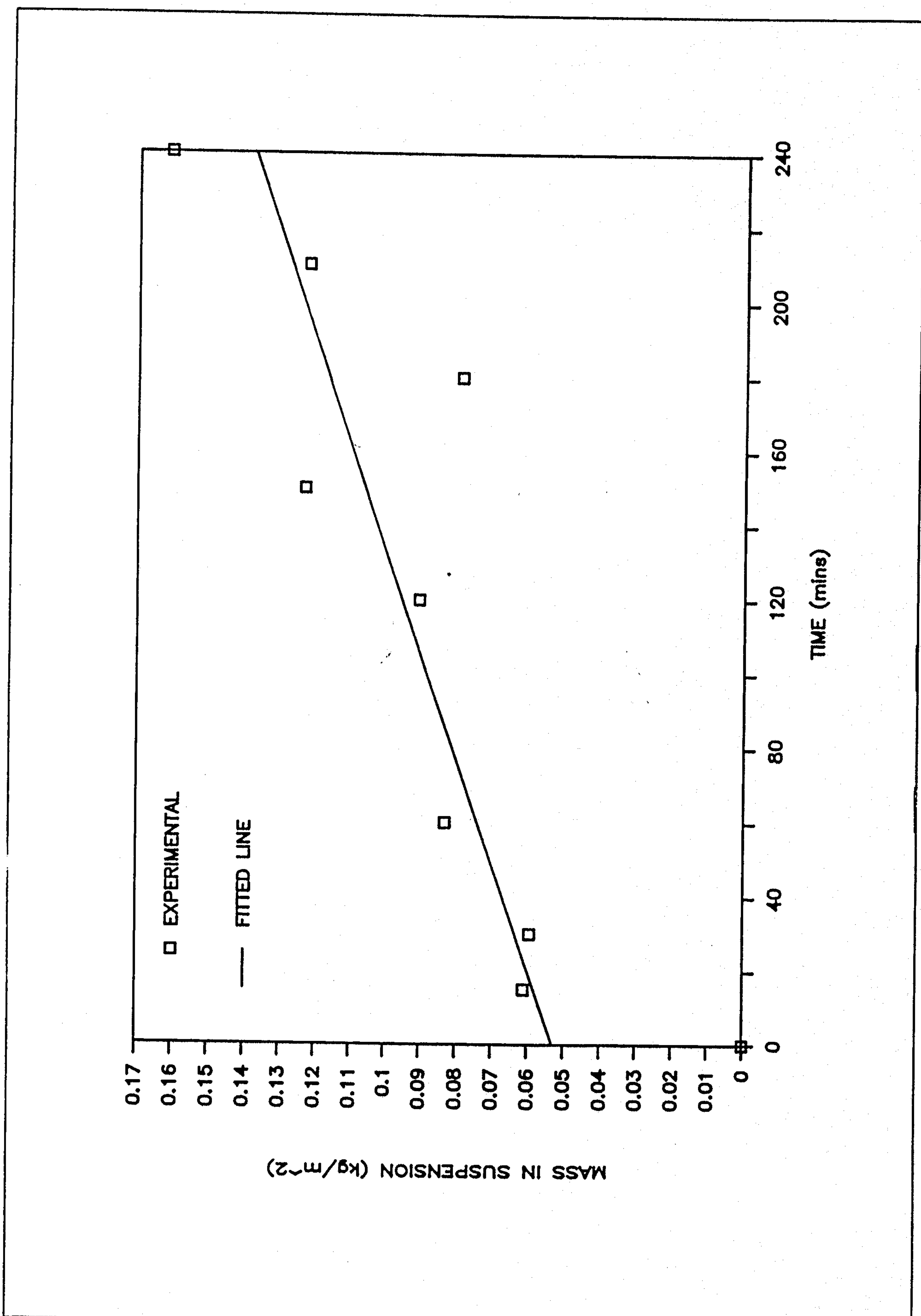

Fig 8 Test A1 mass in suspension against time

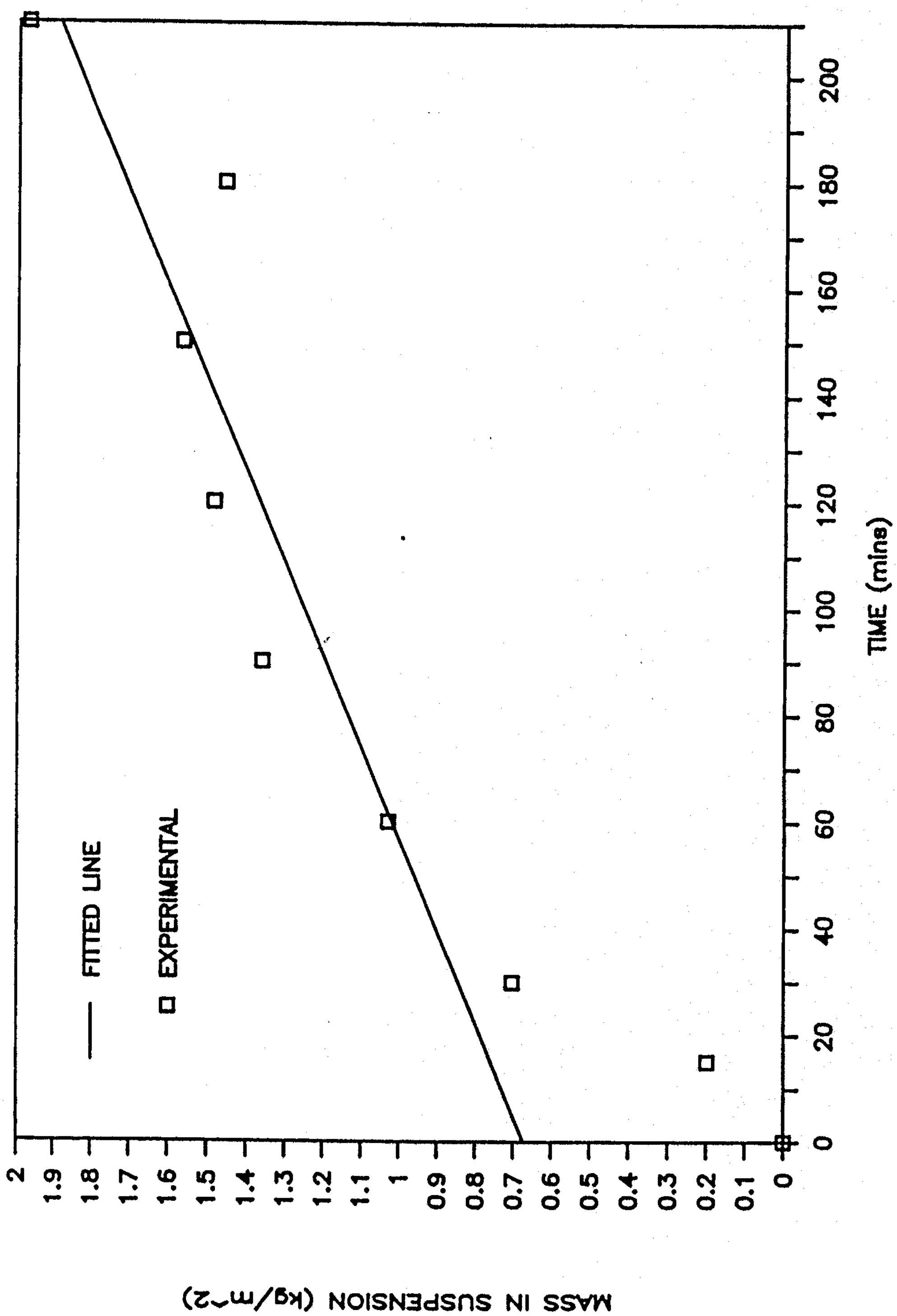

Fig 9 Test A2 mass in suspension against time

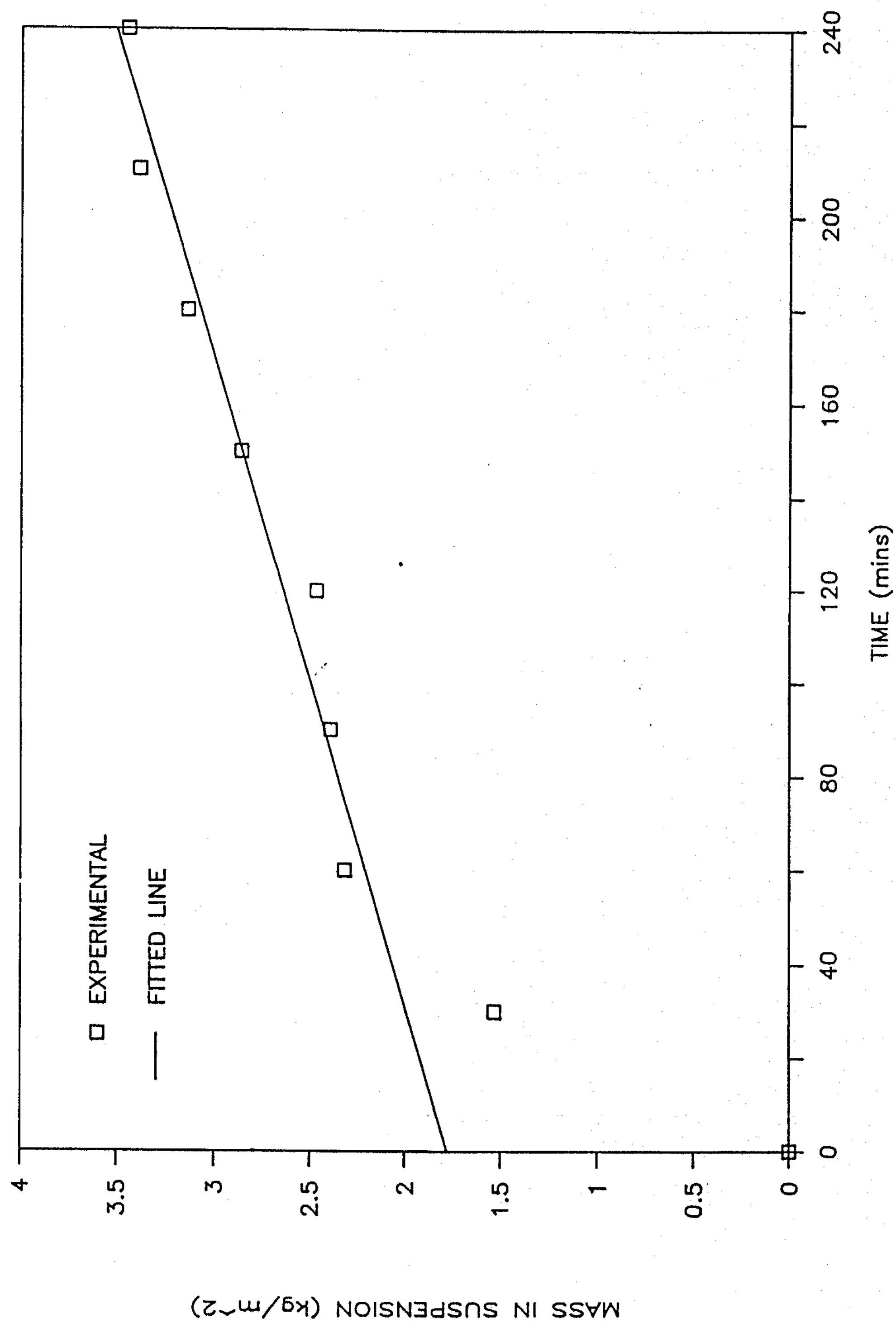

Fig 10 Test A3 mass in suspension against time

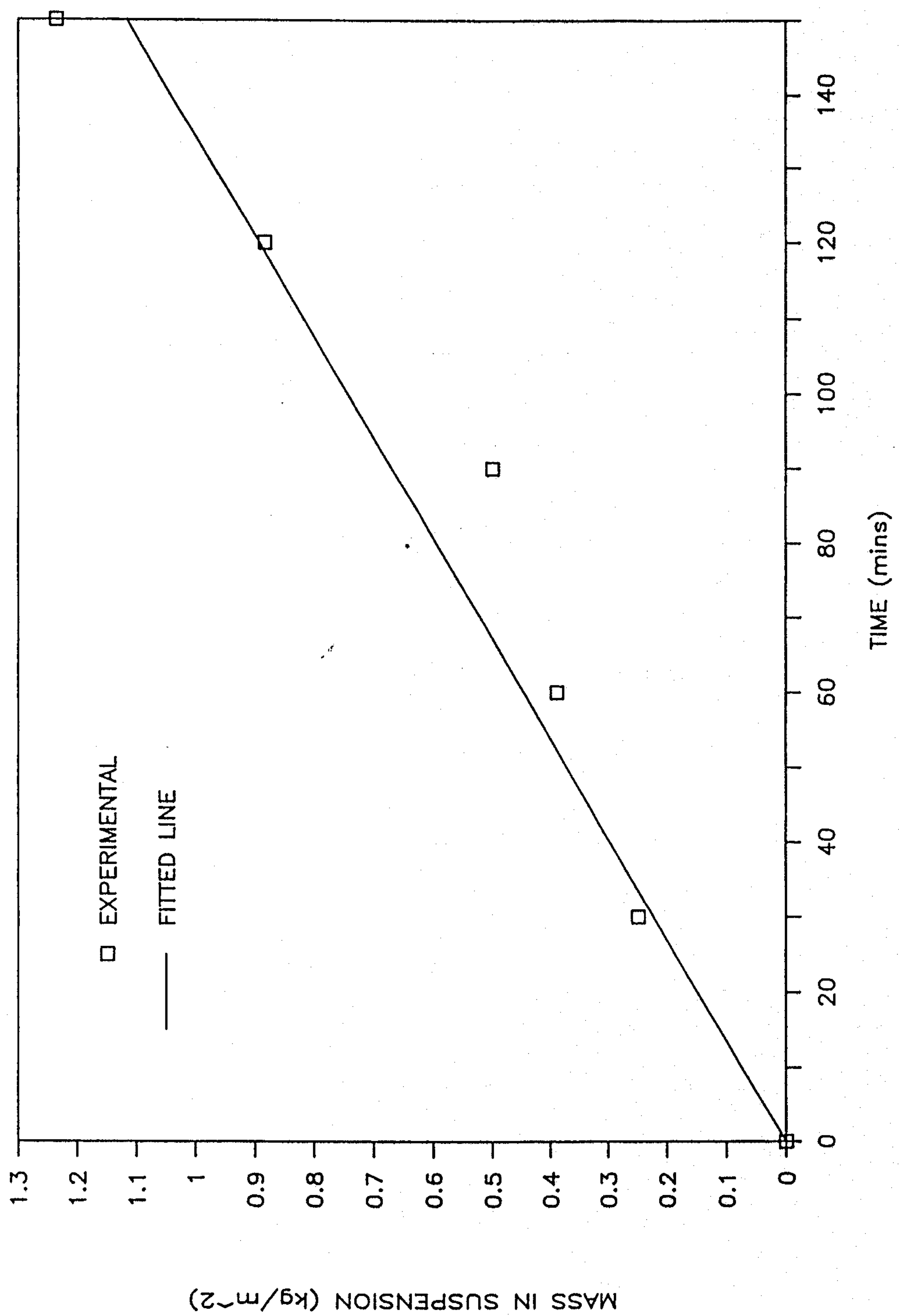

Fig 11 Test A4 mass in suspension against time

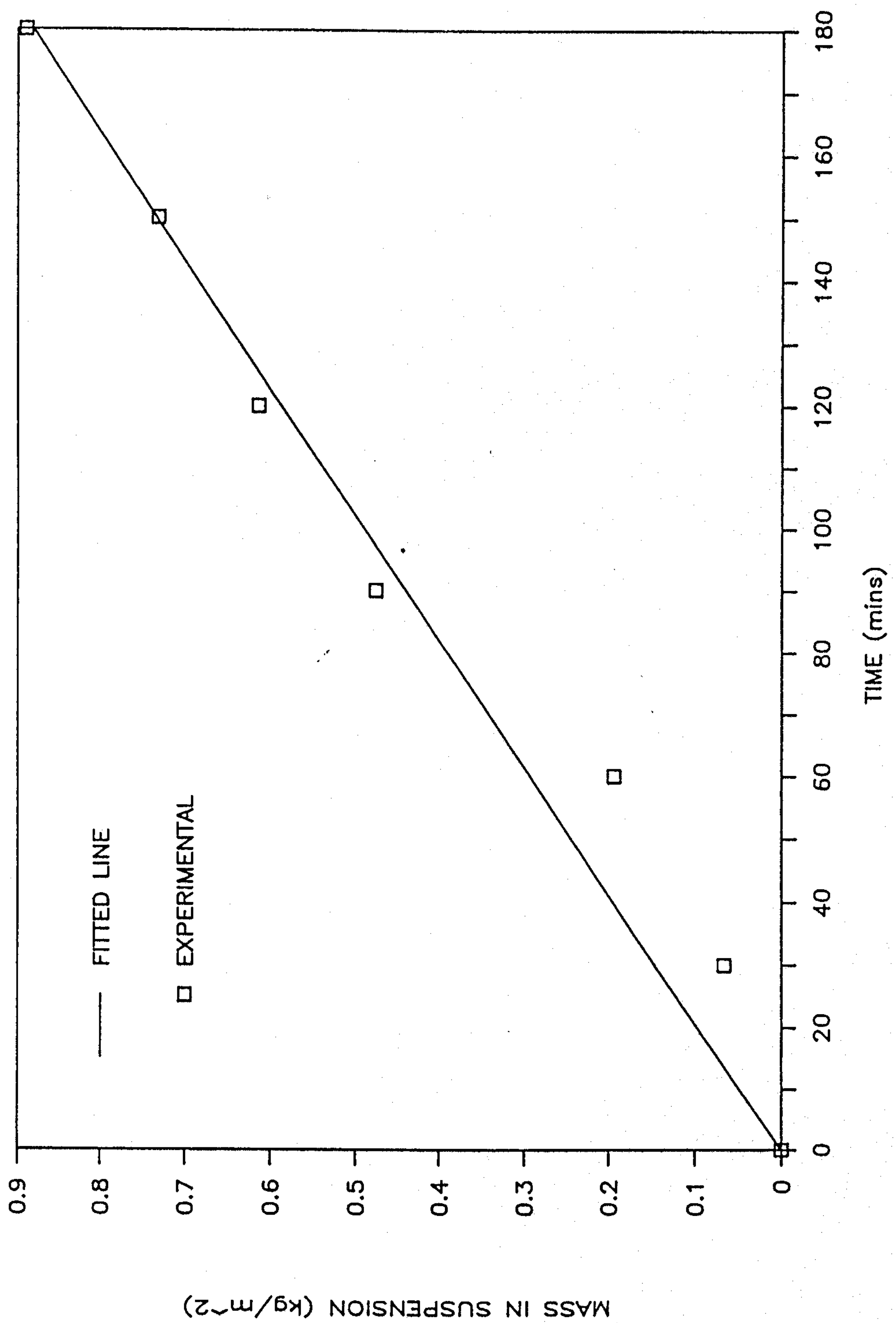

Fig 12 Test A5 mass in suspension against time

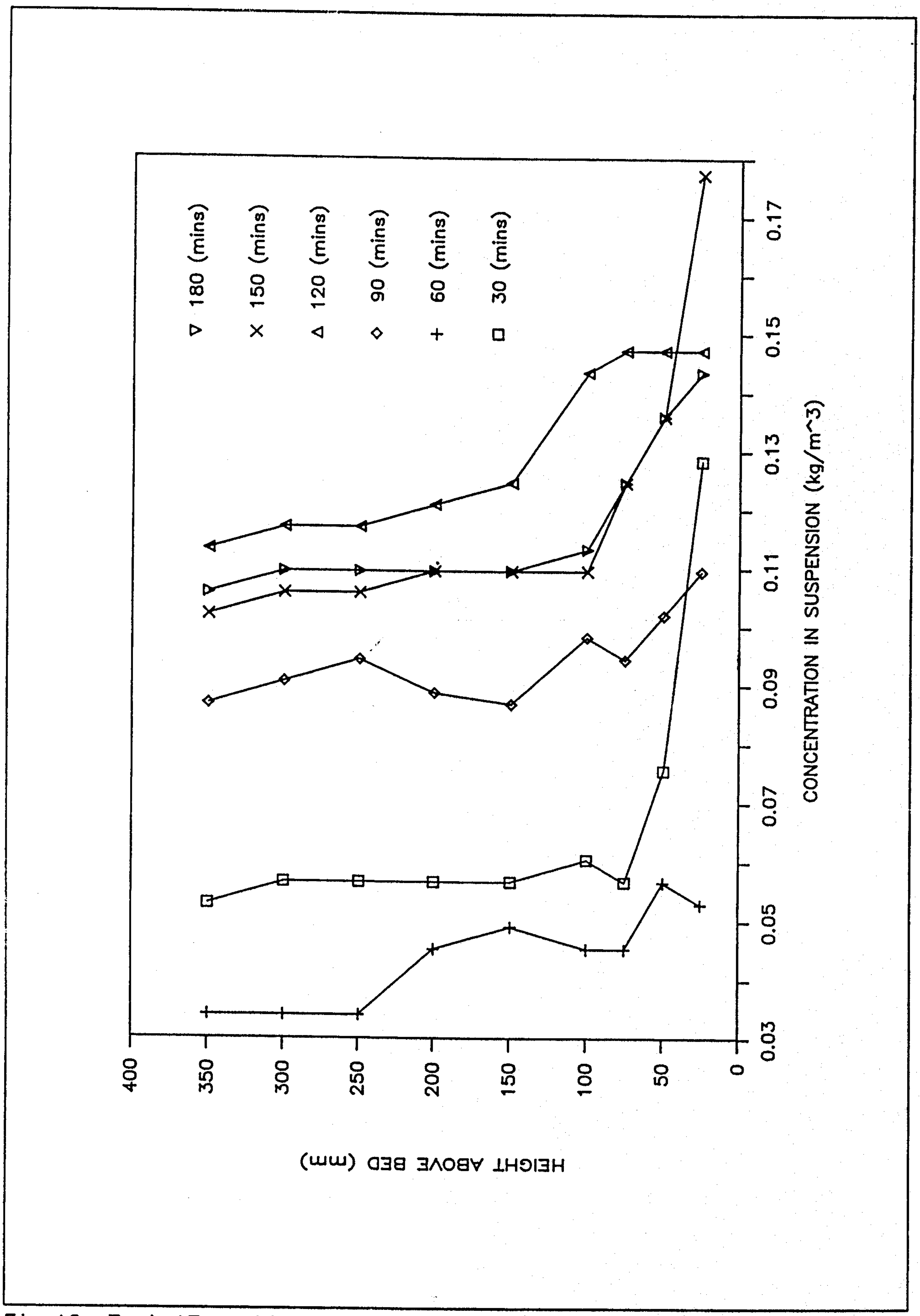

Fig 13 Test A5 vertical concentration profiles

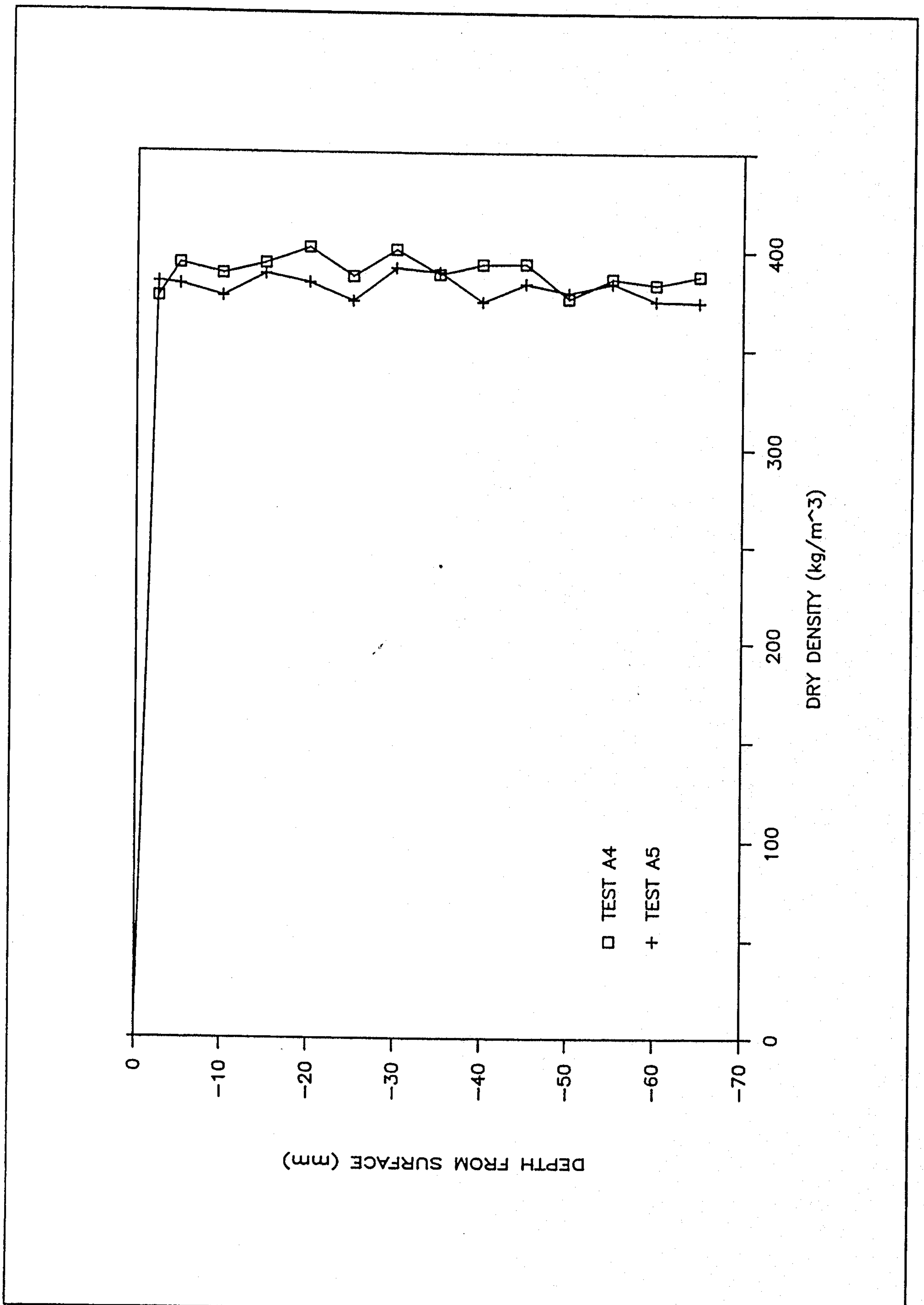

Fig 14 Test A4 and A5 density profiles

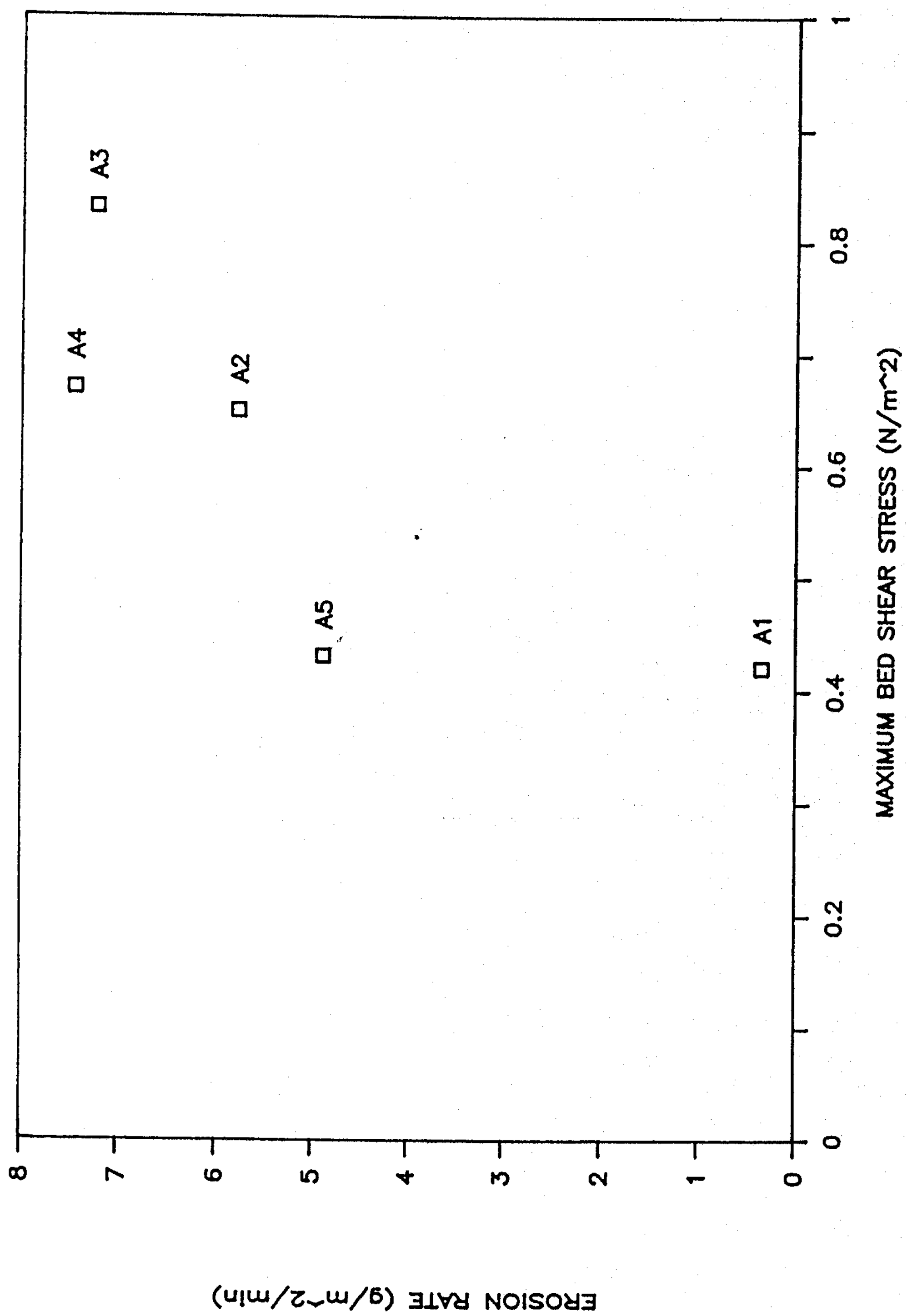

Fig 15 Erosion rate against maximum bed shear stress for all tests

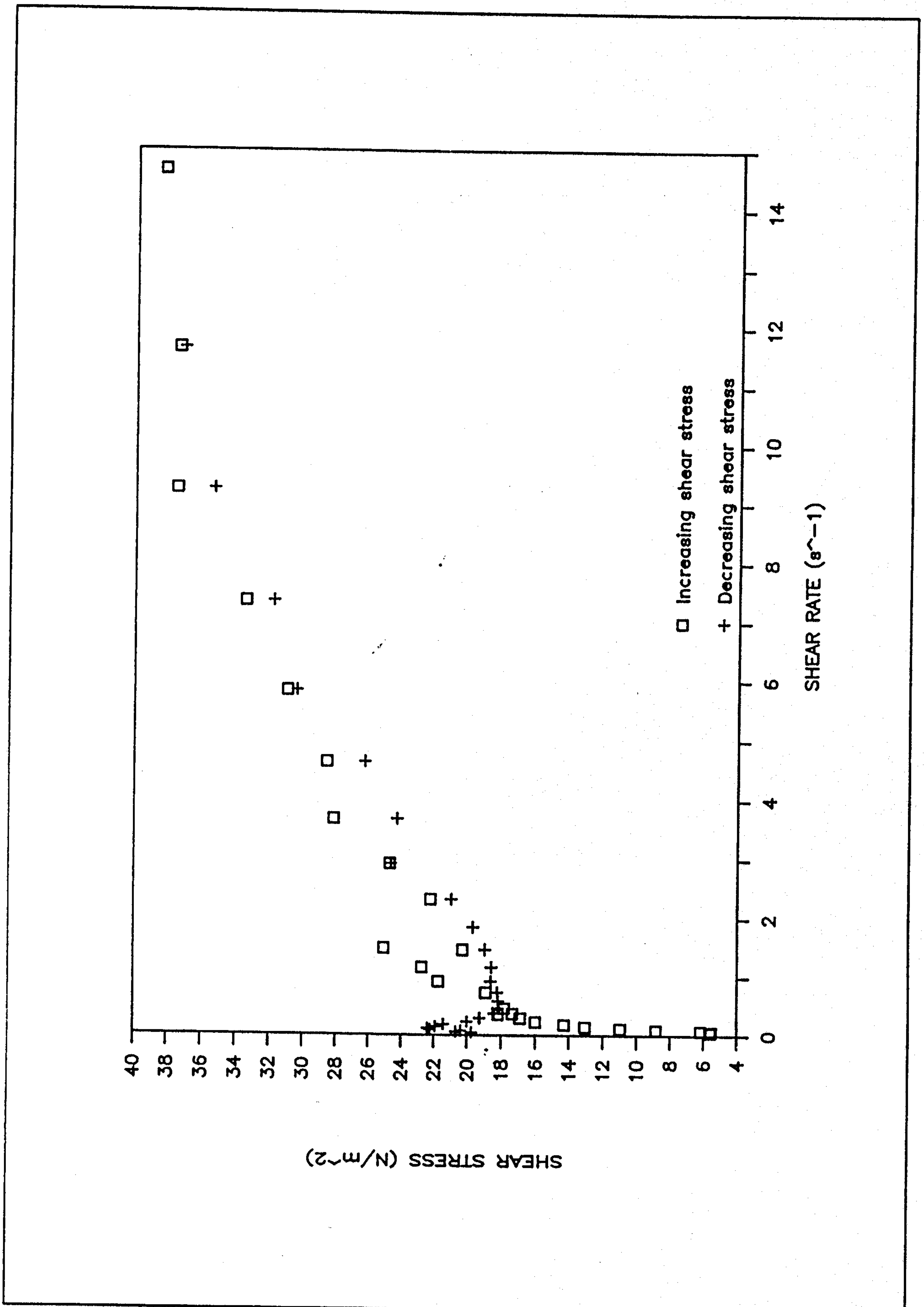

Fig 16 Mud density 350kg/m↑3 shear stress against shear rate

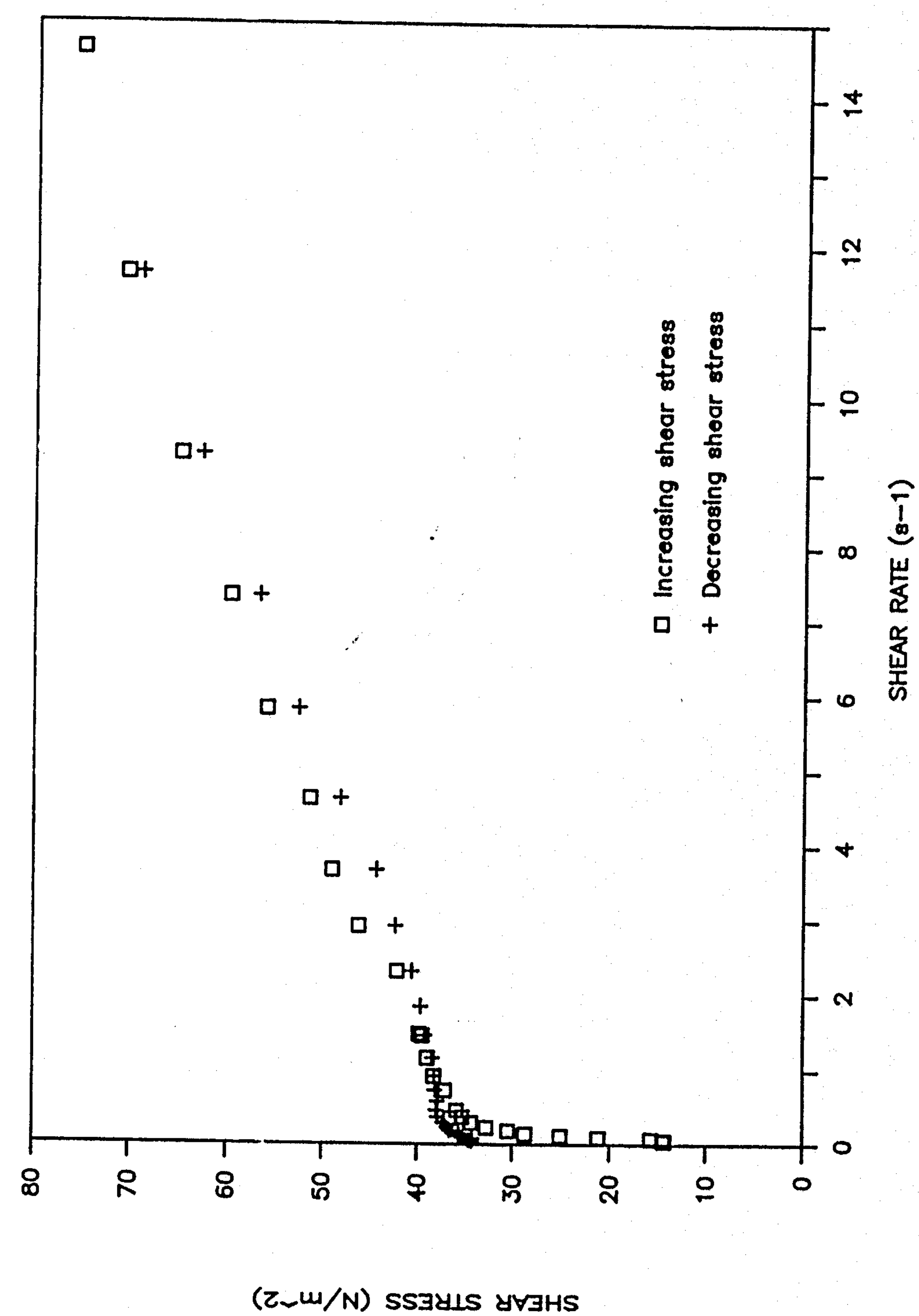

Fig 17 Mud density 400kg/m↑3 shear stress against shear rate

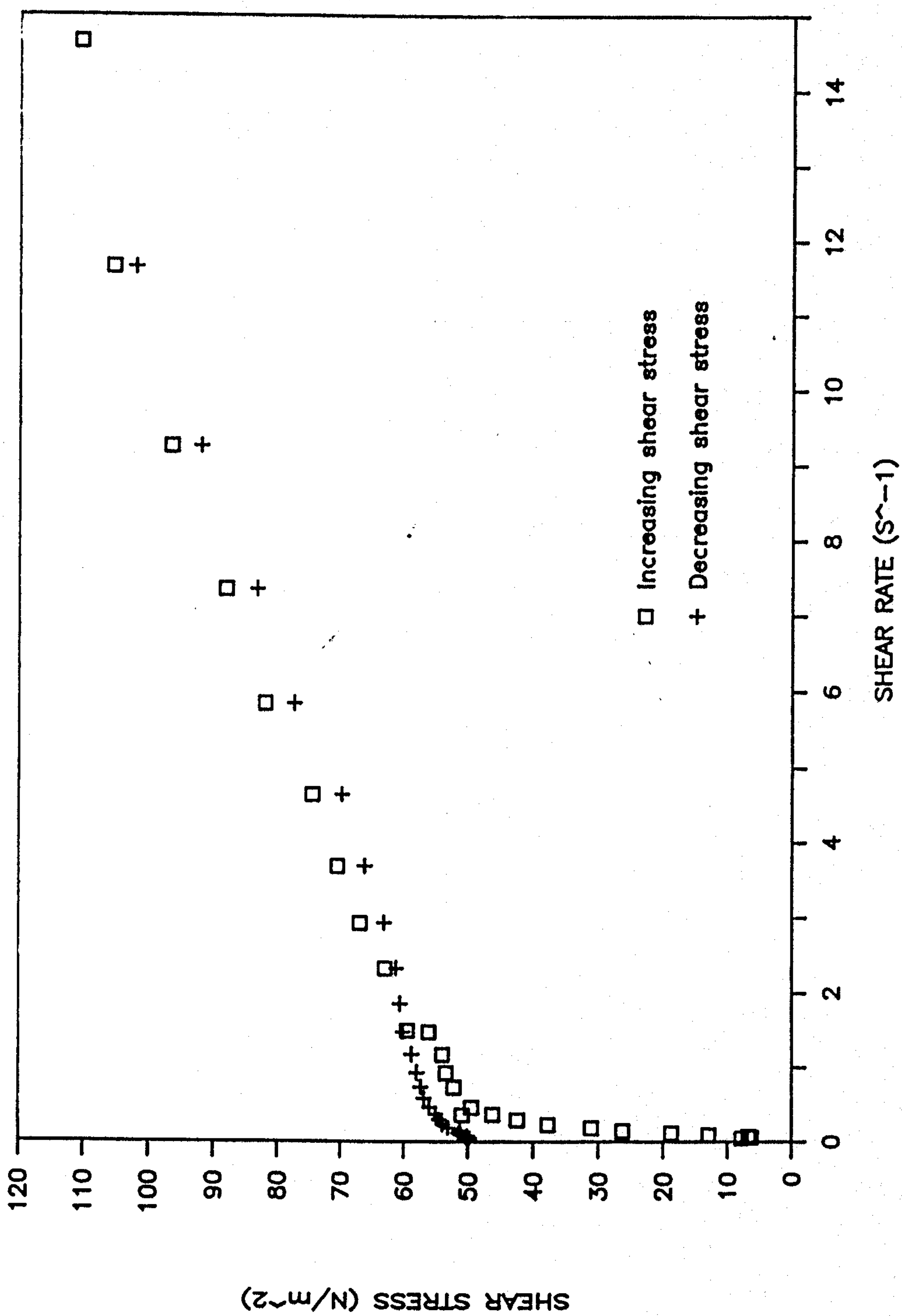

Fig 18 Mud density 460kg/m↑3 shear stress against shear rate

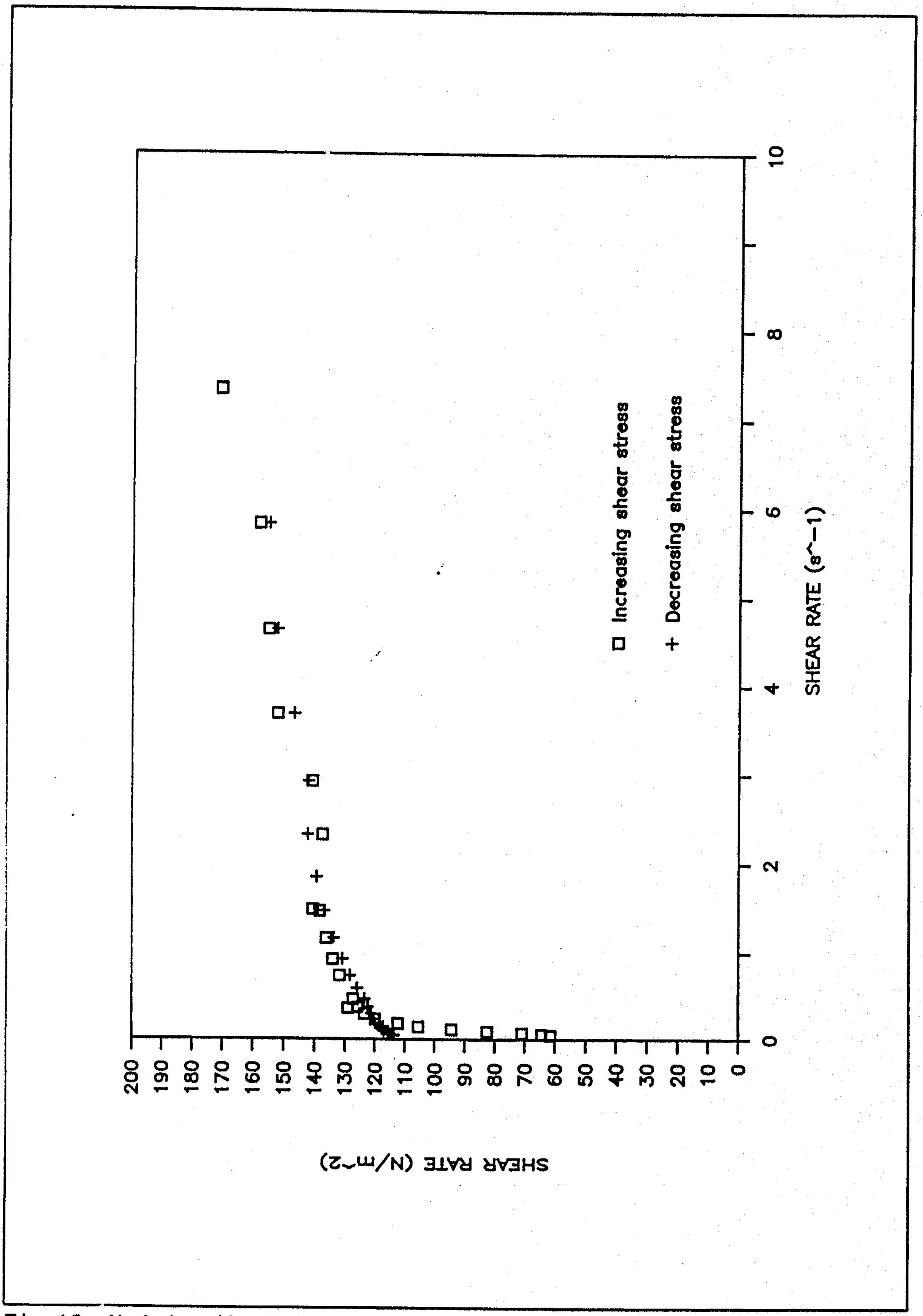

Fig 19 Mud density 510kg/m↑3 shear stress against shear rate

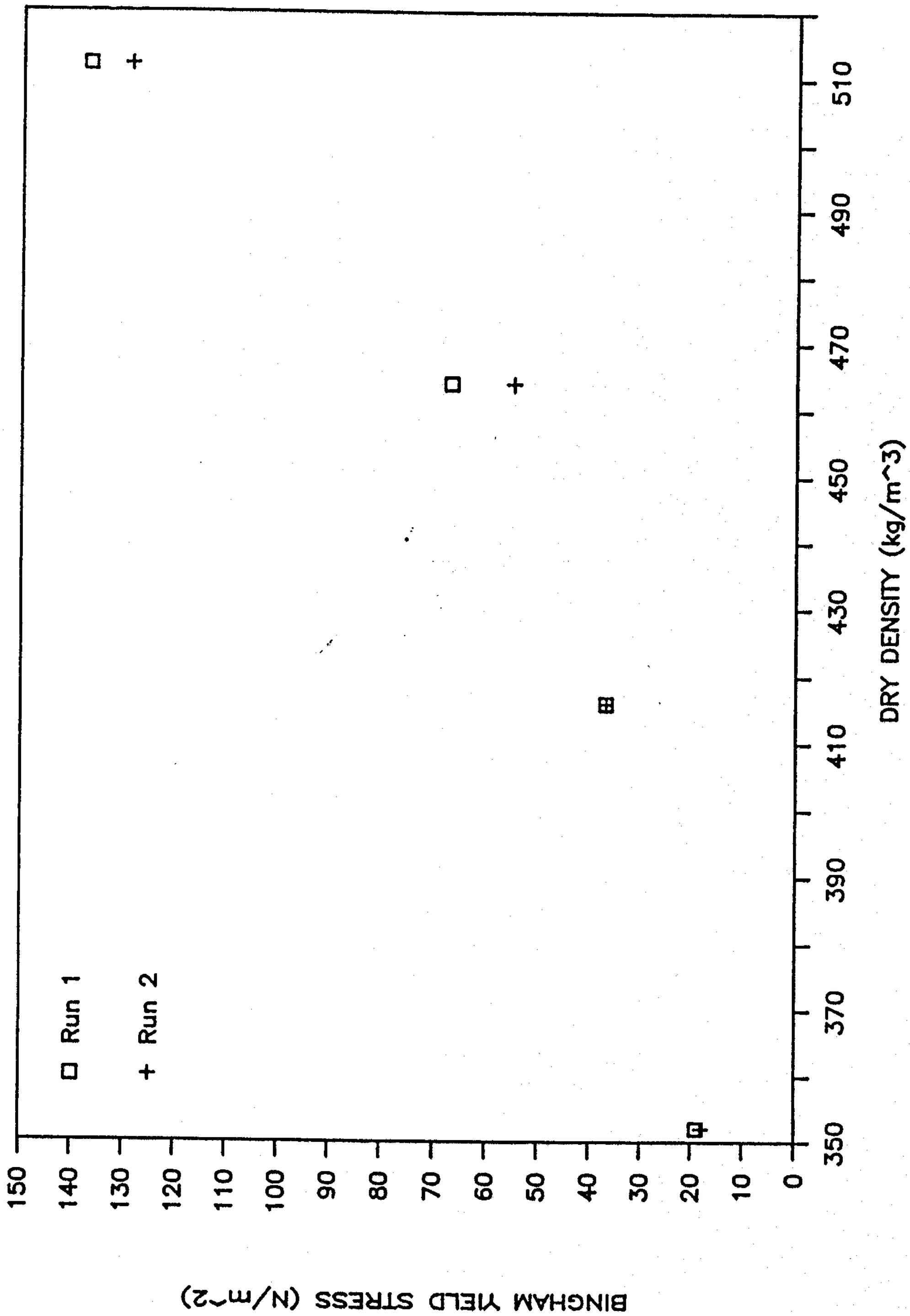

Fig 20 Bingham yield stress against density for bed densities