Hydraulics Research
Wallingford

# SIMULATION AND EXPERIMENTAL DETERMINATION OF A CONSOLIDATING MUD DEPOSIT

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Report No SR 95
July 1987

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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 this report are not necessarily those of the funding Department. The project was carried out by Mr C M Ginger in Dr J G Rodger's section and the experimental work was carried out by Mr A P Diserens and Dr E A Delo 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

A computatronal model was developed to simulate the consolidation of a mud bed formed by repeated deposition of estnarine mud layers. To test the theoretical study, a series of laboratory experiments were undertaken in settling columns. These experiments provided data on the bed density, thickness, mass and void ratio with time.

Previous work on the modelling of consolidation had been confined to mud concentrations much greater thau that found in estuarine environments and consolidation behaviour over long periods of time. Both these parameters of concentration and time are outside the range of practical considerations for an estuary.

This research project deals with suspended mud concentrations within the range encountered in estuaries and also simulates the consolidation path within a much smaller time range (hours to weeks) thus giving a much more usable prediction of the density profile of an estuarine bed deposit. Furthermore this mathematical model simulates the cyclic depositional sequence of an estuary.

The two major areas of interest in the Civil Engineering Industry that are addressed in this research project are the accurate prediction and quantification of the resistance to erosion of the estuarine bed and the dispersal of pollution in the estuary.

The development of this mathematical and subsequent computer model to simulate the consolidation of estuarine sediments will provide the Civil Engineering Industry with a more powerful tool to enhance the industry's current predictions of pollution transport, rate of silting and rate of erosion of estuarine environments.

However, to fully develop this present model it is recommended that further laboratory experimentation and further computer modelling be undertaken together with some field messurements in order to develop a universal programme to cope with the many varied combinations of conditions that could be encountered in the estnarine environment.

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## 1 INTRODUCTION

The consolidation of soil is of great relevance from geological, environmental and engineering points of view, although the timescales involved could vary considerably.

The two major areas of interest in environmental hydraulic engineering with respect to consolidation are resistance to erosion and pollution dispersal.

The erodibility of a mud bed is primarily determined by the shear strength of the exposed bed. This shear strength is related to the density of the mud layer which in turn is related to the degree of consolidation of the bed. Thus, in a consolidating bed the resistance to erosion is a time dependent function of the degree of consolidation.

As a mud deposit consolidates pore water is squeezed out of the bed carrying with it dissolved pollutants. Hence, in evaluating pollution dispersal, the role of fine sediment as a carrier and an exchange medium is affected by the state of consolidation of the bed and its long term consolidation path. Various factors may influence the characteristics of a sediment deposit and hence its long term consolidation path. Amongst these factors the most significant are the rate of sediment deposition and the physical and chemical characteristics of the sediment and water. As a result, the consolidation behaviour of sediment deposits may be site specific and any attempt to model the consolidation process may require detailed field and laboratory experiments for each new site.

## 2 SELF-WEIGHT CONSOLIDATION

Sediment, prior to self weight consolidation, is carried in suspension in moving water until the flow velocity reduces sufficiently to allow particles or flocs to settle on to the bed. The relative motion of water and sediment particles during the processes of settling and consolidation are illustrated schematically in Fig 1. As a particle of material settles through water it does so at a velocity which reflects the balance between gravitational acceleration and the buoyancy and drag forces on the particle. The presence of other particles disturbs this situation by the generation of wakes and pressure forces. With sufficient particles present, they settle more slowly due to the upward flux of water which is being displaced by the settling particles, a condition known as 'hindered settling'. Eventually, when the particles are nearly touching, their settlement is almost entirely controlled by the rate at which water can escape from between them.

In the case of a cohesive sediment, particles come together to form flocs. When the flocs settle, a 'floc blanket' or 'bed' develops. As flocs are added to the blanket, the weight squeezes water out and crushes the flocs as more weight is transferred to them. By this stage, the sediment has ceased to behave as individual flocs but has started to behave as a soil with behaviour described by effective stress theories. However, the soil skeleton in these circumstances is extremely compressible and strains are large. Thus suitable theories to describe this behaviour must include large strain and the body forces of self-weight. Traditional soil consolidation theories are inadequate in both these respects (Ref 2).

A fully saturated soil may be considered as incompressible particles forming a framework whose pore spaces are filled with an incompressible fluid (water). At equilibrium the framework is subjected to a system of stresses. The stresses at any point of a section of the framework can be computed from the total principal stresses, $\sigma_{1,2,3}$, (ie. in each directional plane), which act in this point. The voids filled with water are also under a stress, $U_w$, which acts in all directions in the water and solid. This stress, $U_w$, is the excess pore water pressure. If Uh is the hydrostatic pressure then the difference,

$$\sigma'_{1,2,3} = \sigma_{1,2,3} - U_w - Uh$$

is the effective stress.

Thus it follows that, at equilibrium, the total stress in the '1' direction, at a point, can be written in terms of effective stress as

$$\sigma_{1_0} = \sigma'_{1_0} + U_{w_0} + Uh$$

where subscript '$_0$' refers to equilibrium.

In conditions of one dimensional compression (as in the settling column) if an instantaneous increment, $\Delta\sigma_1$ in the total stress in the '1' direction occurs, the pore water pressure is, by experiment, seen to rise immediately by $\Delta\sigma_1$ (Ref 5). The total stress is now

$$\sigma_{1_0} + \Delta\sigma_1 = \sigma'_{1_0} + (U_{w_0} + \Delta\sigma_1) + Uh$$

With time, the pore pressure returns to its equilibrium value as water drains from the pore spaces and the load is transferred to the particle framework. Thus

$$\sigma_{10} + \Delta\sigma_{10} = (\sigma'_{10} + \Delta\sigma_1) + U_{w0} + Uh$$

With this increasing effective stress the particle framework strains as drainage proceeds and this is accompanied by a decrease in porosity and increasing density (Ref 5).

It is evident, therefore, that changes in soil structure are accompanied by changes in the effective stress ( $\sigma'$ ). This can not be measured, but can only be derived from measurement of the total stress and pore pressure. These measurements are essential for describing any relationships within a consolidating soil stratum.

Looking down into a consolidating bed (Fig 2) there is a transition from a suspension where pore pressure equals total stress and the effective stress is zero, to a situation where the pore pressure becomes less than the total stress and effective stresses start to develop between the particles. As drainage proceeds the effective stresses between the particles increase as the submerged weight of the overlying material is transferred to the soil skeleton. When the pore pressures return to hydrostatic, the effective stress is equal to the submerged weight of the overlying particles.

A variety of approaches have been used to estimate the density and thereby strength of consolidating mud beds and most involve studies of the movement of the sediment/water interface. None of these, however, allow realistic prediction of the depth varying internal density structure of the bed. Only the data of Fuerstenau, reported in Michaels and Bolger (Ref 1) and Parker and Kirby (Ref 2) attempts to measure the density structure and the work of Been and Sills (Ref 3) is the first comprehensive series of tests where full documentation of stress is attempted.

## 3 MATHEMATICAL REPRESENTATION OF CONSOLIDATION

In order to develop a mathematical model for the consolidation of soft compressible soils, Been and Sills (Ref 3) carried out detailed studies on the behaviour of a clay layer formed in a 2m high cylindrical column following a single injection of a uniform slurry. Observations were made of the surface elevation of the deposit, the total stress measured at the base and the density and pore water pressure at various elevations. Consolidation was allowed to continue for periods of up to 100 days.

Several important conclusions can be drawn from the results obtained:

(a) The structure of the deposited material was observed as consisting of a dense bed above which was an intermediate zone in which a loose soil matrix had established itself and finally, above a clearly defined surface, the fluid containing any particles still in suspension. The intermediate zone had very low strength and could readily have been deformed laterally under an imposed shear stress. With time the thickness of the dense bed layer increased and that of the intermediate layer decreased until the latter eventually disappeared.

(b) Reasonably well-defined relationships were found to exist between permeability and voids ratio. The extent to which these relationships depend on the stress history (method of preparation and injection of the slurry) and on the composition of the mud was not investigated.

(c) No unique value of the initial voids ratio was found to exist corresponding to zero effective stress. This was one of the most important findings of the experiments and led Been and Sills to incorporate an "imaginary overburden" in order to obtain a solution to the theoretical equations.

(d) The concentration of the initial suspension and the formation of flocs play an important role in determining whether the composition of the settled bed is homogeneous. Where the concentration is low or the particles in suspension are fully dispersed, a clear variation in size grading occurs through the bed whereas beds formed from dense flocculated suspensions show little variation.

In order to develop mathematical functions for use in the simulation of consolidation, Figures 14 and 16 from Been and Sills (Ref 3) were used as presented in Figure 3 and sample functions have been fitted to the original data points on both the permeability and effective stress plots. These have the following mathematical forms (Ref 4).

**Permeability**

$$k = 0.1 \times 10^{(\log_{10}e - 2.5)/0.3} \text{ m/s}$$

$$k = 10^{(\log_{10}3 - 2.5)/0.3} \text{ m/s}$$

and

**Effective stress**

$$\sigma' = 3/e^2 \text{ KN/m}^2$$

$$\sigma' = 6/e^2 \ KN/m^2$$

These equations form the basis for the computer model developed to simulate consolidation under estuarine conditions. These equations also formed the basis of the model developed by E Atkinson (Ref 4) for the consolidation of reservoir sediments.

The functions used in the computer model are

**Permeability**

$$K = PF \times 0.1 \times 10^{(\log_{10} e - 2.5)/0.3} \quad m/$$

**Effective stress**

$$\sigma' = SF \times 3/e^2 \ kN/m^2$$

where PF is the permeability factor which ranges from 1 to 10 to cover the full range of permeability functions and SF is the stress factor which ranges from 1 to 2 and covers the full range of effective stress functions. These factors can be varied to match the properties of the mud being investigated.

## 4 A THEORETICAL COMPUTER MODEL

Some previous work on developing a computer model for consolidation was carried out by Atkinson (Ref 4) on predicting the behaviour of self consolidating sediments in reservoirs. To date, there has been no model developed which can predict the behaviour of a bed subject to tidal accretion and associated consolidation. In order to explain how the present model is derived it is necessary to introduce some additional common soil mechanics terms.

(i) Voids ratio (e) is defined for a completely saturated soil as:

$$e = \frac{\text{volume of water}}{\text{volume of solids}} \quad (1)$$

(ii) Permeability (k) provides a measure of the resistance of soil to the passage of water. The permeability is defined as:

$$k = \frac{v}{i} \quad (2)$$

where

v = relative velocity of the water to the soil

$$= \frac{\text{volumetric flow rate}}{\text{total area (including both particles and pores)}}$$

i = hydraulic gradient

$$= \frac{\text{difference in head between 2 points}}{\text{distance between the points}} \quad (3)$$

$$= \frac{\Delta h}{\Delta s}$$

Permeability is measured in units of velocity, m/s.

(iii) Specific Bulk Density which is defined as:

$$\frac{\text{Bulk density of the soil}}{\text{Density of Water}} \quad (5)$$

To develop a model which can approximately predict the behaviour of a bed of self-consolidating soil, three simplifying assumptions have been made:

(1) that there is a unique relationship between the voids ratio and the permeability for a particular soil, whatever its history (see Fig 3).

(2) that there is a similar unique relationship between the voids ratio and the effective stress, (see Fig 3).

(3) that the bed of consolidating soil can be considered to be made up of layers, each with a certain voids ratio (and therefore unique values of k, $\sigma'$ and density) and pore pressure. This is shown diagramatically in Figure 4.

The flow of water out of layer j and into layer (j + 1) in Figure 4 can be taken approximately as :

$v_j$ = Artificial velocity of water leaving layer j

$$= \frac{k_j \, (U_j - U_{j+1})}{x_j \, \gamma_w} \qquad (6)$$

where $\gamma_w$ = specific weight of water.

This is derived from equations (2) and (3) where

$$\Delta h = \frac{(U_j - U_{j+1})}{\gamma_w} \qquad (7)$$

and

$$\Delta s = x_j = \text{the thickness of layer j} \qquad (8)$$

After a short time interval, $\Delta t$, $x_j$ has changed slightly as a result of consolidation so that, from conservation, its new value becomes:

$$(x_j)\text{new} = (x_j)\text{old} - (V_j - V_{j-1}) \; \Delta t \qquad (9)$$

The total quantity of soil in the layer has not changed so a new voids ratio ($e_j$) can be found because it is proportional to $x_j$ (10)

Therefore,

$$e_j = \frac{x_j (1 + e_o)}{x_o} - 1$$

where $e_o$ and $x_o$ are the initial conditions.

Density and voids ratio are clearly related for a given soil and the function may be expressed as:

$$\text{Specific bulk density} = \frac{G_s + e}{1 + e} \qquad (12)$$

where

$$G_s = \frac{\text{density of solids}}{\text{density of water}} \qquad (13)$$

$G_s$ = specific gravity of solids

The effective stress and permeability of a soil layer with a given voids ratio can be determined on the basis of the assumed relations

$$\sigma' = \text{function } (e) \qquad (14)$$

and

$$k = \text{function } (e) \qquad (15)$$

Also, the total stress at any layer may be found by integrating the densities of all layers above it, and multiplying by g (=9.81 $m/s^2$). The new excess pore pressures may then be determined by rewriting equation (4) as:

$$u_j = \sigma_j - \sigma_j' - Uh \qquad (16)$$

Thus, by applying equations (6) to (16) a new set of pore pressures can be determined in each layer after the passage of a small time interval.

To operate the model suitable boundary conditions must be selected. The upper boundary conditions, where the deposition of fresh sediment is occurring, is set by two parameters; firstly, the initial voids ratio, $e_o$, which is the void ratio before any consolidation occurs, and secondly the water pressure at the surface, $U_{ho} = 0$. This assumption is considered reasonable because the change in hydrostatic pressure over a small time period is negligible and only the difference in pore pressure is used in calculating the velocity of water leaving a layer (Equation 6).

The lower boundary condition can be taken as a rigid impermeable surface, that is $V = 0$. Whether seepage is, in fact, negligible will depend on the soil below the deposited bed. If it were sand it would be unsafe to regard it as impermeable.

## 5 INTERPRETATION OF RESULTS OF COMPUTER MODEL

To obtain a reasonably accurate solution using this method a vast number of calculations are required. The analysis was, therefore, undertaken by computer. The input for the computer programme is as follows:

- the form of the function $k(e)$
- the form of the function $\sigma'(e)$
- the rate of soil deposition in $kg/m^2/day$
- the voids ratio of the soil at deposition ($e_o$)
- the age at which the simulation stops

- the age at which consolidation results are required

The k(e) and $\sigma'$(e) functions were obtained from Been and Sills (Ref 3), Figures 14 and 16. However, their data was based on values of e ranging from 3 to 16, whereas in the present study, voids ratios over a much wider range need to be considered. There was therefore insufficient data available to determine values of e, k and $\sigma$ in the lower and upper layers of the bed where the simulation gave values of e much smaller and greater respectively than in the experimental results obtained by Been and Sills (Ref 3). The values adopted in such cases were based on extrapolation of the published data and should be treated with caution.

In order to make the simulated results directly comparable to the experimental results a further programme was written to plot the simulated density profile to the scale of the experimental plots. This programme converts the depth of each layer from the top of the bed to the height of each layer from the bottom of the bed and also plots the simulated density value in the middle of each layer. Furthermore, because the density on the top of the highest layer is set using the void ratio as the initial void ratio ($e_o$), the density value for the highest layer is plotted at a height of 0.33 times the height of the top layer from the bottom of the top layer.

## 6 SIMULATIONS - DATA AND RESULTS

Varying modes of sediment deposition as well as different depositional rates were investigated using the computer model. The permeability and effective stress functions determined from Figure 3 are as follows:

$k = PF \times 0.1 \times 10^{(\log_{10} e - 2.5)/0.3}$ m/

$\sigma' = SF \times 3/e^2$ kN/m$^2$

The programme developed to simulate consolidation was fine tuned by varying the input parameters to simulate varying rates of deposition, void ratios, length of consolidation as well as varying the boundary conditions on top of the bed by controlling the velocity of water leaving the top layer of the bed and the model results compared with some preliminary laboratory data.

On completion of the above fine tuning a further three simulations were carried out using laboratory experimental data from experiments carried out by Hydraulics Research Ltd in order to compare the simulated results with experimental results.

Simulation 1, 2 and 3 correspond to laboratory experiments 6, 7 and 8 respectively.

Simulation 1

Rate of deposition - 7.2kg/m$^2$/day for the first hour, 19.2kg/m$^2$/day for the next hour and 5.4kg/m$^2$/day for the next 2 hours.
Initial void ratio - 30
Age at end of simulation - 7 days

The length of simulation varied from 1 day to 7 days.
Note: Simulation 1 represents laboratory experiment Test 6.

Simulation 2

Rate of deposition - 72kg/m$^2$/day for the first one and a half hours

Initial void ratio - 50

Age at end of simulation - 1 day

This simulation was carried out in conjunction with an experiment to draw a comparison between predicted and experimental data. The experimental results were obtained after 24 hours consolidation.

Note: Simulation 7 represents laboratory experiment Test 7.

Simulation 3

Rate of deposition - 36.0kg/m$^2$/day for the first hour, 24.0kg/m$^2$/day for the second hour, 13.2kg/m$^2$/day for the third hour and 7.8kg/m$^2$/day for the fourth hour.

Initial voids ratio - 100

Age at end of simulation - 7 days

This simulation was carried out in conjunction with an experiment to draw a comparison between predicted and experimental data.

The length of simulation varied from 1 day to 4 days.

Note: Simulation 3 represents laboratory experiment Test 8.

Varying the inputs to the simulation produces effects which can largely be understood in terms of physical processes.

Firstly, an increase in the rate of deposition for a given permeability in the surface layer, results in a reduction in the mean rate of consolidation and, therefore, the mean bulk density.

Secondly, an increase in the age of the deposit results in relatively lower densities compared to the initial densities in the upper sediment layers. This arises because water seeping from lower layers enters the upper layers causing a reduction in their net rate of water loss, and consequently, in their rate of consolidation.

Thirdly, an increase in initial voids ratio produces larger voids ratios at all depths for the same age of consolidated bed.

Finally, changes in the functions for both permeability and effective stress cause changes in the density profile; an increase in permeability for a given e allows more rapid consolidation and so produces higher densities. An accurate specification of the functional dependence of the permeability on the voids ratio is therefore essential if the consolidation process is to be modelled accurately.

## 7 SETTLING AND CONSOLIDATION TESTS

Tests 1-5 - single suspension

The first five experiments were undertaken to examine the effect of variations in the depth and suspended solids concentration in the initial water column on the rate of deposition and the initial voids ratio.

Test 1

A suspension of $0.983kg/m^3$ mud in saline solution (approx $35kg/m^3$ NaCl) was placed in a settling column to a depth of 2 metres. Bed thickness and density profiles were measured at various times during deposition and consolidation. The test was ended after 3 days.

**Test 2**

A suspension of approximately twice the concentration of that used in Test 1 ($1.9 kg/m^3$) was introduced into the column to a depth of 1 metre (giving approximately the same total mass as in Test 1). The experiment was monitored during deposition and consolidation as in Test 1.

**Test 3**

A suspension of half the concentration of Test 1 was introduced into a 4m settling column (giving approximately the same total mass of sediment as in Test 1) and monitored as in Test 1.

**Test 4**

This was a repeat of Test 1 to examine the repeatability of the test results.

**Test 5**

The same height of column as Test 1 was used (2 metres) with twice the concentration of suspension (giving twice the total mass) and once again monitored for bed thickness and density profiles throughout settling and consolidation for a period of 3 days.

See Appendix A for further details.

Tests 6 - 8 repeated consolidations

Test 6 to 8 aimed to simulate settling and consolidation of a bed with a periodic deposition of sediment. The top meter of a 2m water column was replaced with a mud suspension of fixed concentration, from a stock suspension, at time intervals of 24 hours (see Fig 5). This resulted in the addition of a new layer of mud each day to the bed. The density profile of the bed was measured before the addition of the new suspension each day. The density profile was also measured during settlement and consolidation of the first layer. It was observed that virtually all the sediment had settled in a twenty four hour period.

**Test 6**

A stock suspension of approximately 1.37kg/m$^3$ was used giving a deposition rate of around 1.37kg/m$^2$ of bed per day. The test was continued for four days.

**Test 7**

A stock suspension of approximately 4.12kg/m$^3$ was used giving a deposition rate of about 4.12kg/m$^2$ of bed per day. The test was continued for 2 days.

**Test 8**

A stock suspension of approximately 3.61kg/m$^3$ was used giving a deposition rate of 3.61kg/m$^2$ of bed per day. This test was continued for 4 days.

See Appendix A for further details.

## 8 RESULTS OF LABORATORY EXPERIMENTS

The bed thickness, mass and voids ratio were plotted as a function of time for experiments 1-5 (Figs A1-A5 in Appendix A). From the data collected the density profile for test 1-5 were plotted (Figs A6-A10 in

Appendix A). The bed thickness, mass and voids ratio were plotted as a function of time for experiments 6-8 (Fig A11-A13 in Appendix A). The density profiles for tests 6-8 were also plotted (Figs A14-A16 in Appendix A).

It was found that the initial (and, hence final) voids ratio was affected slightly by the rate of deposition. Beds deposited faster had slightly lower initial voids ratios than those deposited more slowly (experiments 1-3), although the differences were not very great.

The repetition of Test 1 as Test 4 showed some variation although the final density profile was within the standard deviation of the density readings.

Test 5 had a similar initial concentration as Test 2 but twice the total mass as a result of using twice the volume. It was found that the larger total mass and so bed depth resulted in higher final densities.

The density profiles for 24 hourly intervals were plotted for Test 6 and 8 (Figs A14-A16 in Appendix A). Each new addition of sediment was assumed to have the same initial voids ratio and deposition rate because they originated from the same prepared sample as in the initial column.

## 9 COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS

Tests 6 and 8 were suitable for comparison as density profiles were available on a continuing basis. Test 6 was continued for four days and the density profiles were taken after one, two, three and six days were compared with the simulated profiles (see Figs 6A, 6B, 6C, 6D) and found to correlate to a high degree of accuracy.

Test 7 was continued for 2 days and the density profile obtained after consolidation for one day was compared with the simulated profile (see Fig 7). Test 8 was continued for 4 days and the density profiles obtained after one, two, three and four days were compared with the simulated profiles (see Figs 8A, 8B, 8C, 8D). When comparing the simulated and observed density profiles it should be borne in mind that the simulated results are based on the following assumptions.

(a) The mud bed is homogeneous both in the vertical and horizontal directions.

(b) Each deposition forms a uniform bed of uniform thickness throughout.

Under experimental conditions distinct layering is observed (see Plate 2). This would suggest some degree of segregation of particles and hence nonuniformity. This effect would suggest that the density profile obtained from experimentation would vary from that simulated as follows:-

(a) The experimental density at the bottom of the layer would be greater than the simulated density because of the more rapid consolidation of the larger particles (see Fig 8A).

(b) The experimental density near the top of the first layer would be less than that simulated because the finer particles at the top would be less consolidated than that predicted by the simulation (see Fig 8A).

(c) With subsequent depositions this density variation will be observed but with the bottom of one layer and the top of the layer below interacting to give a higher observing density than predicted in the vicinity of the bed interfaces (see Fig 8D).

Furthermore it is apparent that layer thickness is not uniform for all of the experiments (see Plate 3). This too would influence the correlation between the observed and simulated density profiles.

Taking these factors into account it is considered that the simulated density profile fits the experimental results well and could be used as a tool in predicting the density profiles in an estuary sufficiently well for engineering purposes.

## 10 SUMMARY AND CONCLUSIONS

The previous sections have outlined the experimental and theoretical work undertaken in this research project.

The computer simulations covered a wide range of deposition rates and void ratios. The lower range of deposition rates were of the order of those found in estuaries and hence represented a very useful area of research.

The void ratios were initially assumed to be as high as 130 and subsequently a value of 90 to 100 was used after analysing the experimental results.

The correlation between experimental and simulated results was good, especially if the scatter or error in measuring densities is taken into account.

On the experimental results the following observations are made.

1. Overburden is the prime force causing consolidation but is only transmitted as the effective stress. The two are only equal when excess pore pressure is zero, ie. consolidation is complete.

2. The consolidation rate of a particular layer depends on the number and thicknesses of underlying layers and their degree of consolidation.

3. Segregation of material during settling produces small sub- layers within the overall density profile. The coarser layers will (i) exhibit less strain, (ii) contribute more load per unit height (being denser) and (iii) will be more permeable.

4. It is misleading to express a density profile in dimensionless terms for a consolidating bed because the absolute bed thickness governs, at least partly, its consolidation rate. It may be valid for comparing fully consolidated beds.

5. The self-weight consolidation theory of Been and Sills (Ref 3) describes the mechanisms which operate in single event experiments but the physical circumstances in these experiments, and probably also in nature introduce important

differences. The effects of mineral segregation means that the mass/unit volume relationship through any one layer is not constant for the same degree of consolidation. Similarly the compressibility of the layers under given stress conditions varies.

6. In a consolidating mud bed, the structure and its attendant properties change with time. Thus, if a mud bed is prepared for erosion studies, for example, it should be ensured that the stress conditions in it are similar to those in the field. This means knowing the total stress and pore pressure in-situ and representing these in the laboratory. Thus it is of great importance when trying to study the consolidation of suspensions to be in a position to say what the general stress situation in the bed is and particularly whether consolidation is complete or not. Instrumentation of the experiments with pore pressure and total stress transducers is essential.

## 11 RECOMMENDATIONS FOR FUTURE WORK

- Further work in verifying the computer programme to simulate very low deposition rates is required.

- The programme should be expanded to take concentrations of sediment in solution rather than deposition rates.

- A facility to simulate re-entrainment of sediment is required.

Further experimentation is required to better define the effective stress voids ratio relationship at higher and lower voids ratios than that presently available.

To allow a complete and adequate description of the experiment, measurements of all components of the stress system should be made as follows:

**Total stress:** This should be measured using a total stress transducer in the base of the column. The proportion of the total weight measured by the transducer will be affected by wall friction. This can be evaluated by integration of the density profile to obtain an alternative measurement of total stress. The diameter of the tube will also influence the wall friction as a function of surface area. This should be examined by comparison of settlement with different diameter tubes for the same mass of sediment.

**Density:** This is currently the principal parameter of interest in relating bed structure to erodibility. It is also required to calculate the total stress profile by integration. Measurement should be made with high spatial resolution (±0.002m) and should be made rapidly and in a continuous profile. Measurements should be sufficiently rapid that no significant change in density in the profile occurs during the period of the profile. Continuous measurement is needed to identify all structural elements in a profile.

Pore water pressure: It is absolutely essential that the vertical distribution of pore water pressure should be measured to:

(a) allow calculation of the effective stresses

(b) establish when consolidation is complete.

The measurements of the three parameters is the minimum that is acceptable as a description of the experiments. Only density was measured in the series of experiments examined herein. These conditions lead to the following specific recommendations for uprating the experimental facility.

(a) Replacement of the bottom 2 metres of the jointed column with a continuous acrylic column.

(b) Automation of the density profiling system over this bottom two metres by using displacement transducers connected to an X-Y plotter to plot count rate profiles, and to a mini/micro computer to digitise the count rate profiles.

(c) Refurbishment of the density measuring system to improve its response time and resolution.

(d) Instrumentation of the lower 2 metres of the column with pore pressure ports, a basal total stress transducer, and self sealing ports for sampling or other intrusive measurements.

(e) Installation of facilities for introduction of material at varying rates using pumps and suitable control systems.

The following laboratory programme is recommended:

A series of experiments to investigate the density and effective stress structures developed under typical estuarine sedimentation conditions. These experiments are to be undertaken in conjunction with the installations of pore-pressure ports to allow evaluation of the state of consolidation of the bed and a total stress transducer in the base of the column to measure total stress.

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FIGURES

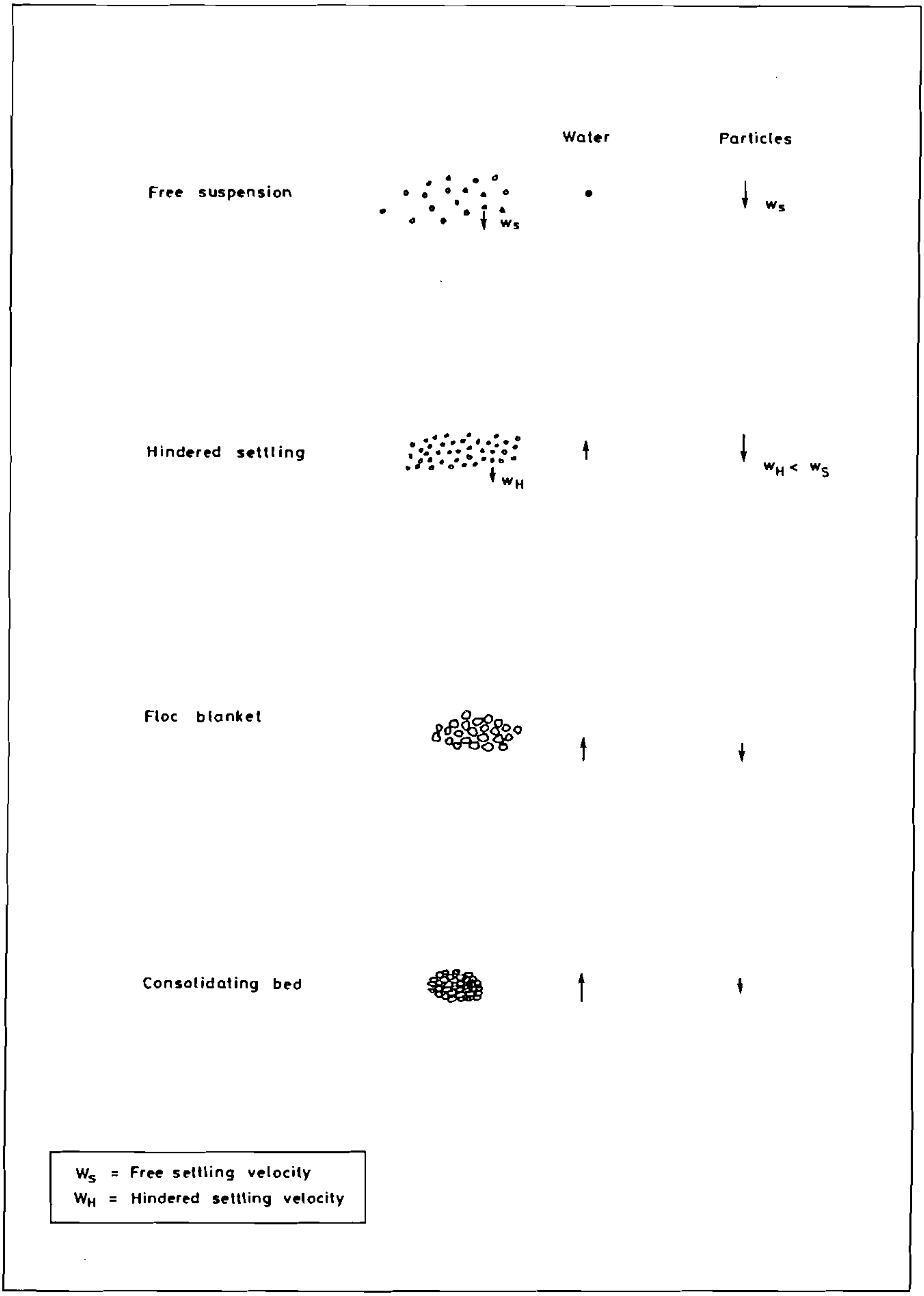
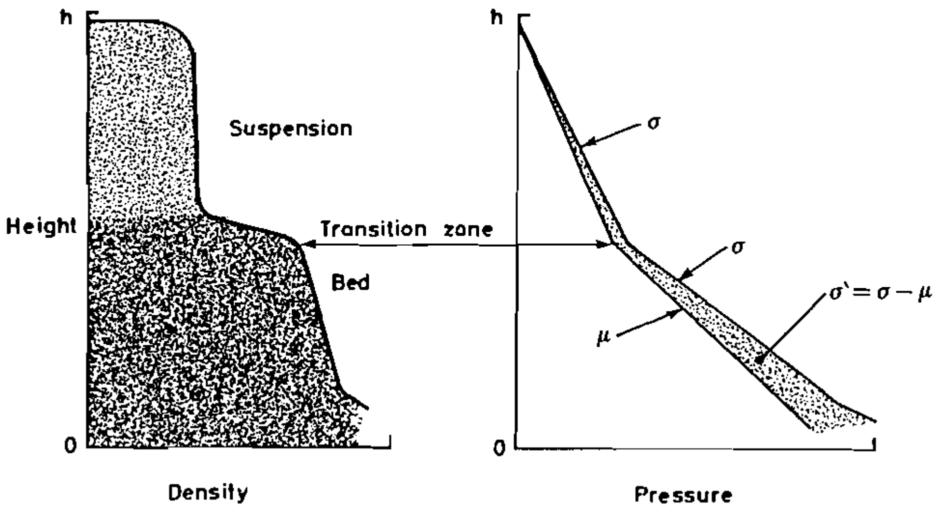



Fig 1 Relative motion of water and sediment (REF 4)

Note that in the suspension, although the density is almost constant with depth the total stress increases more rapidly than the excess pore pressure such that some effective stress between the particles appears to exist. This trend increases markedly further into bed




σ' Effective stress
σ Total stress
μ Hydrostatic pressure
After Been and Sills[2]

Fig 2 Density and pressure in a consolidating suspension (REF4)

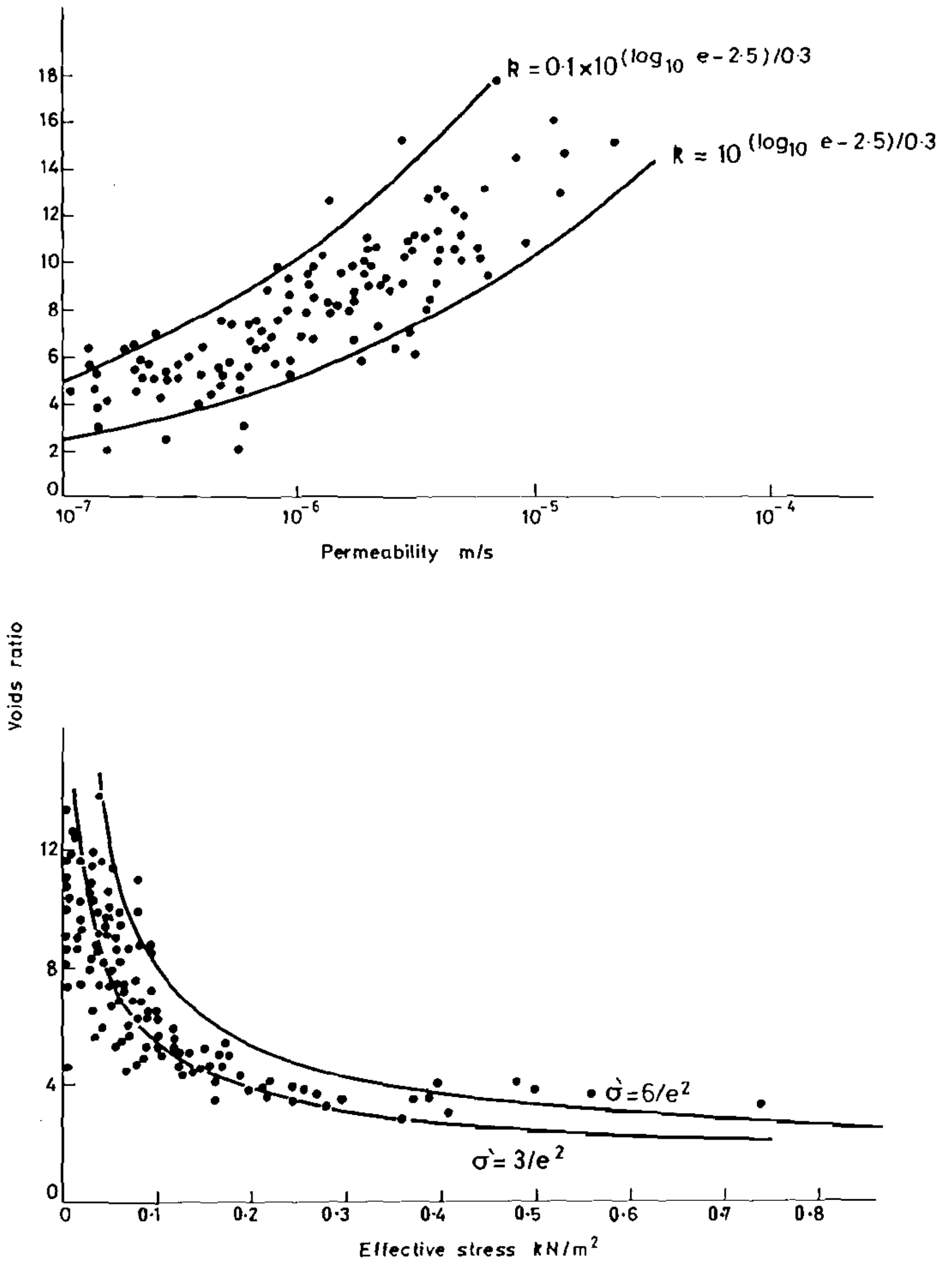



Fig 3 The permeability and effective stress functions

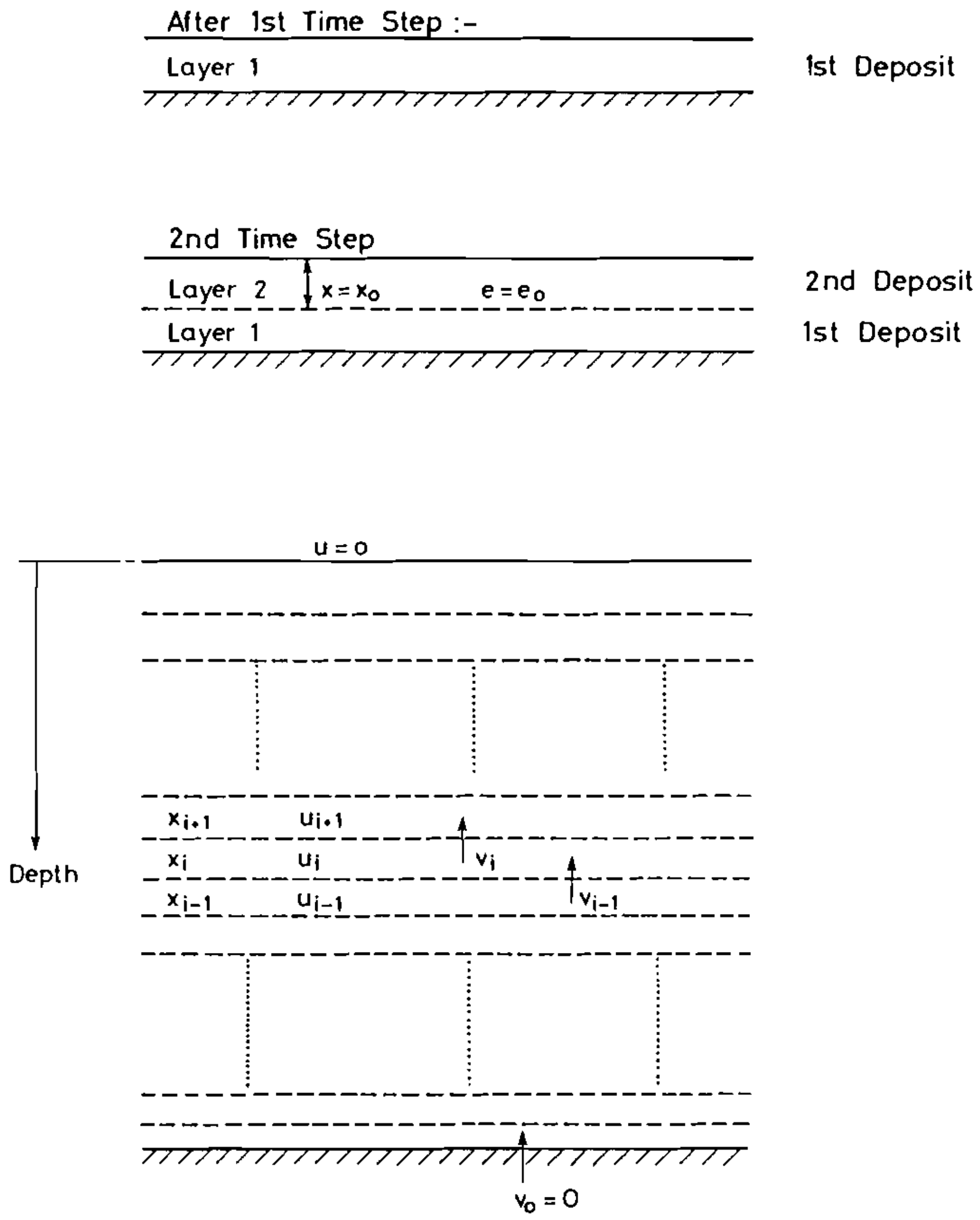



Fig 4 Splitting the bed into layers (REF 4)

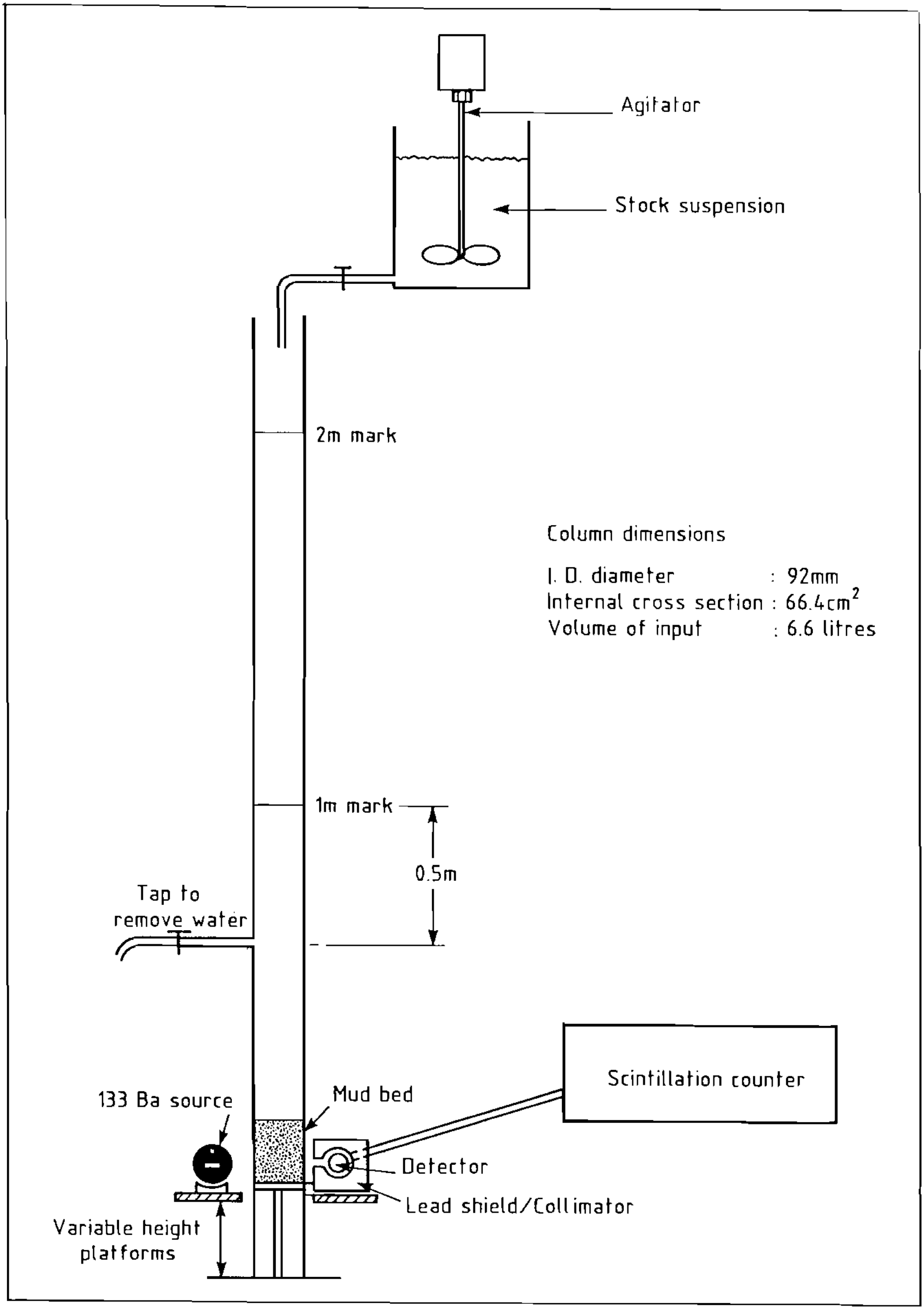



Fig 5 Settling column apparatus

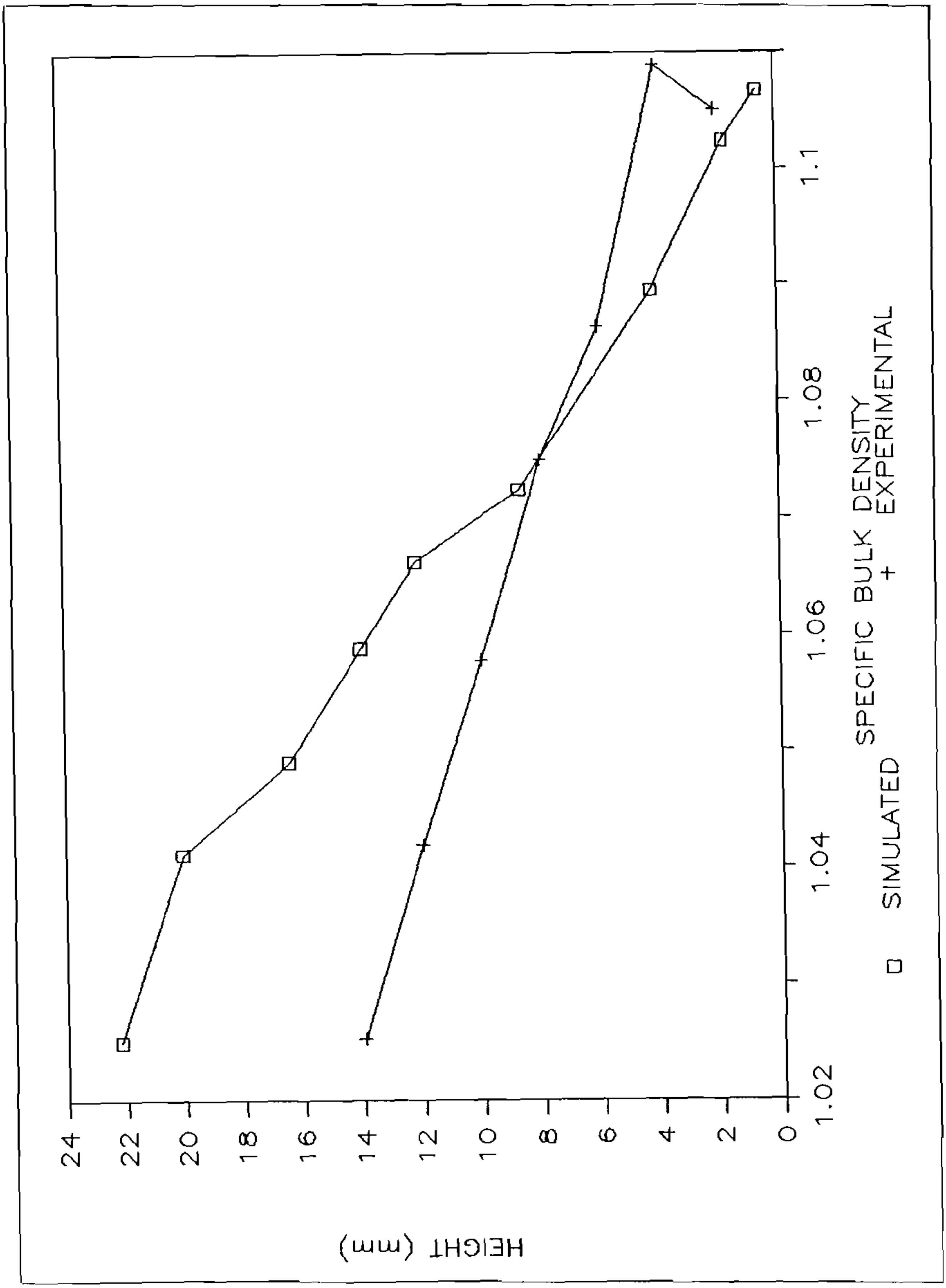



Fig 6A Test 6. Comparison of simulated and experimental bulk density profiles. Time = 24 hours

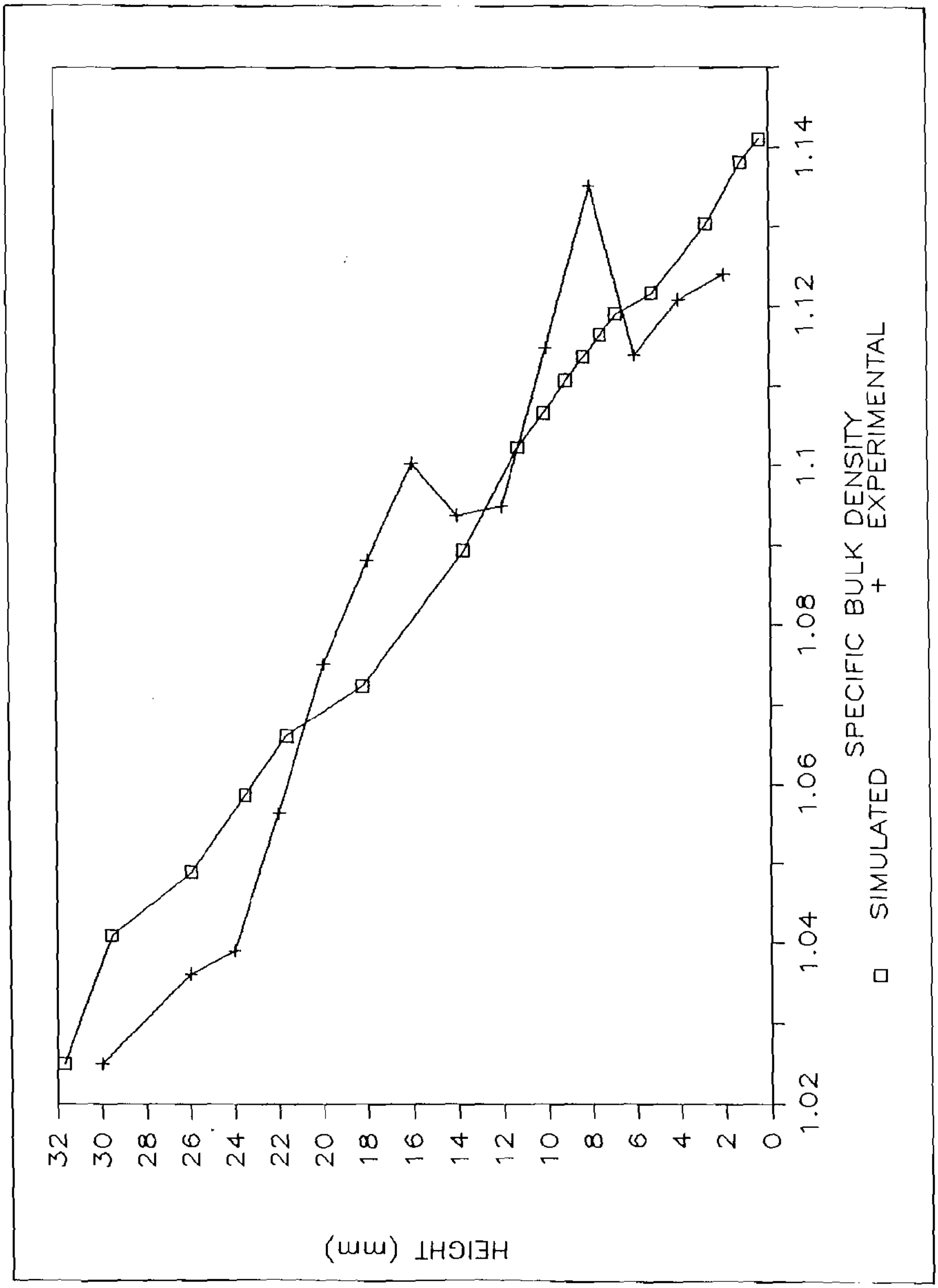



Fig 6B Test 6. Comparison of simulated and experimental bulk density profiles. Time = 48 hours

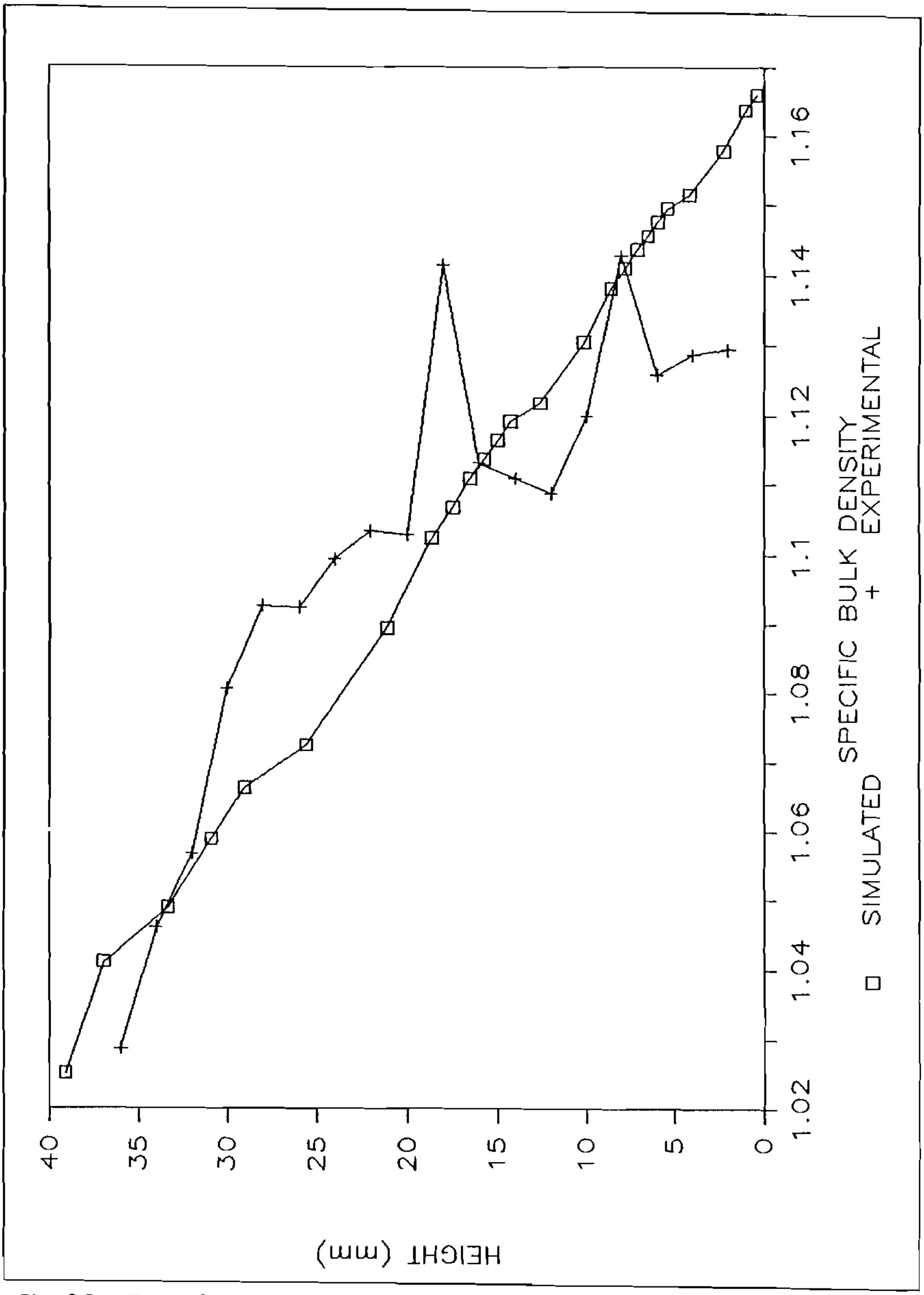



Fig 6C Test 6. Comparison of simulated and experimental bulk density profiles. Time = 72 hours

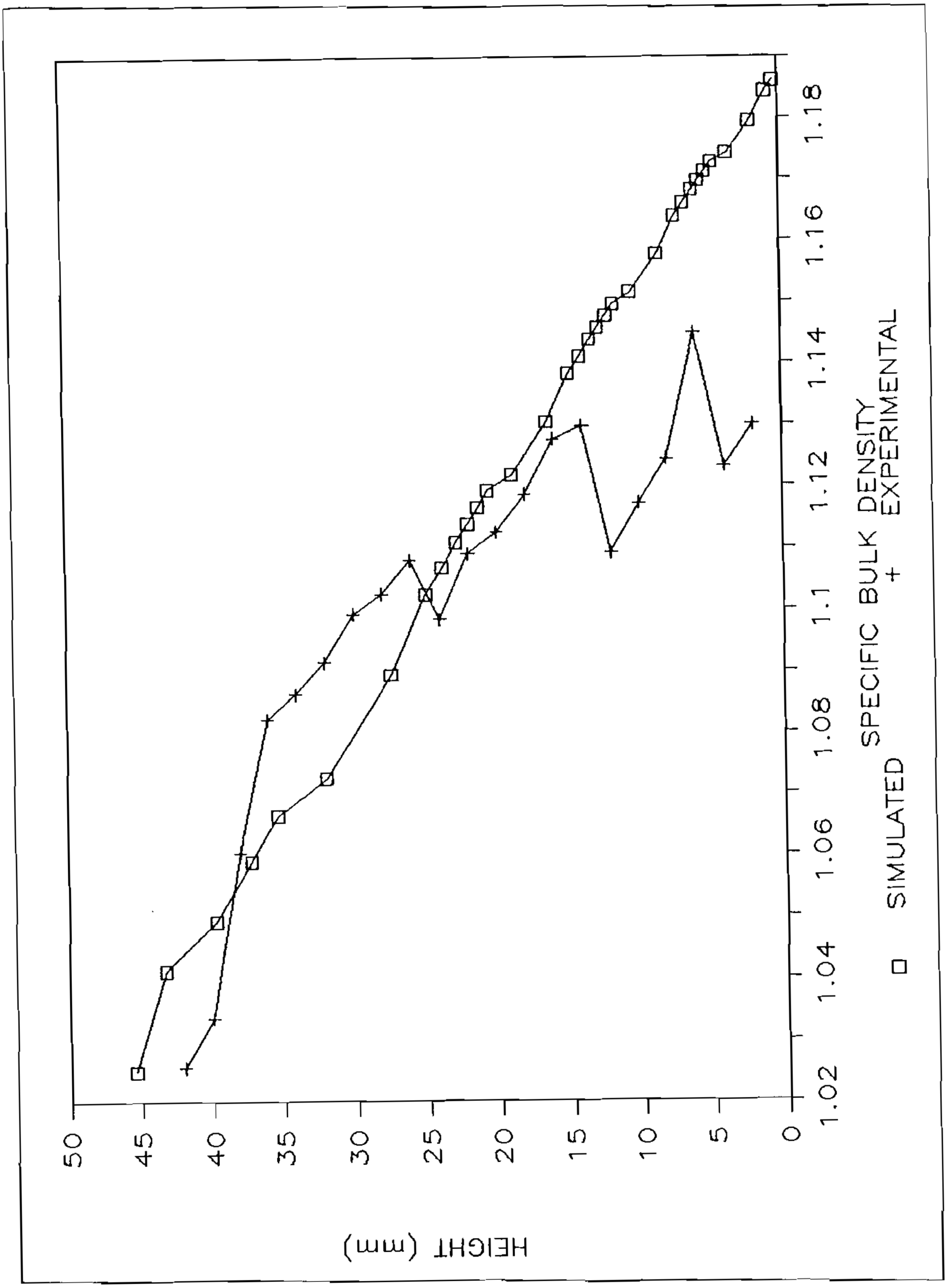



Fig 6D Test 6. Comparison of simulated and experimental bulk density profiles. Time =144 hours

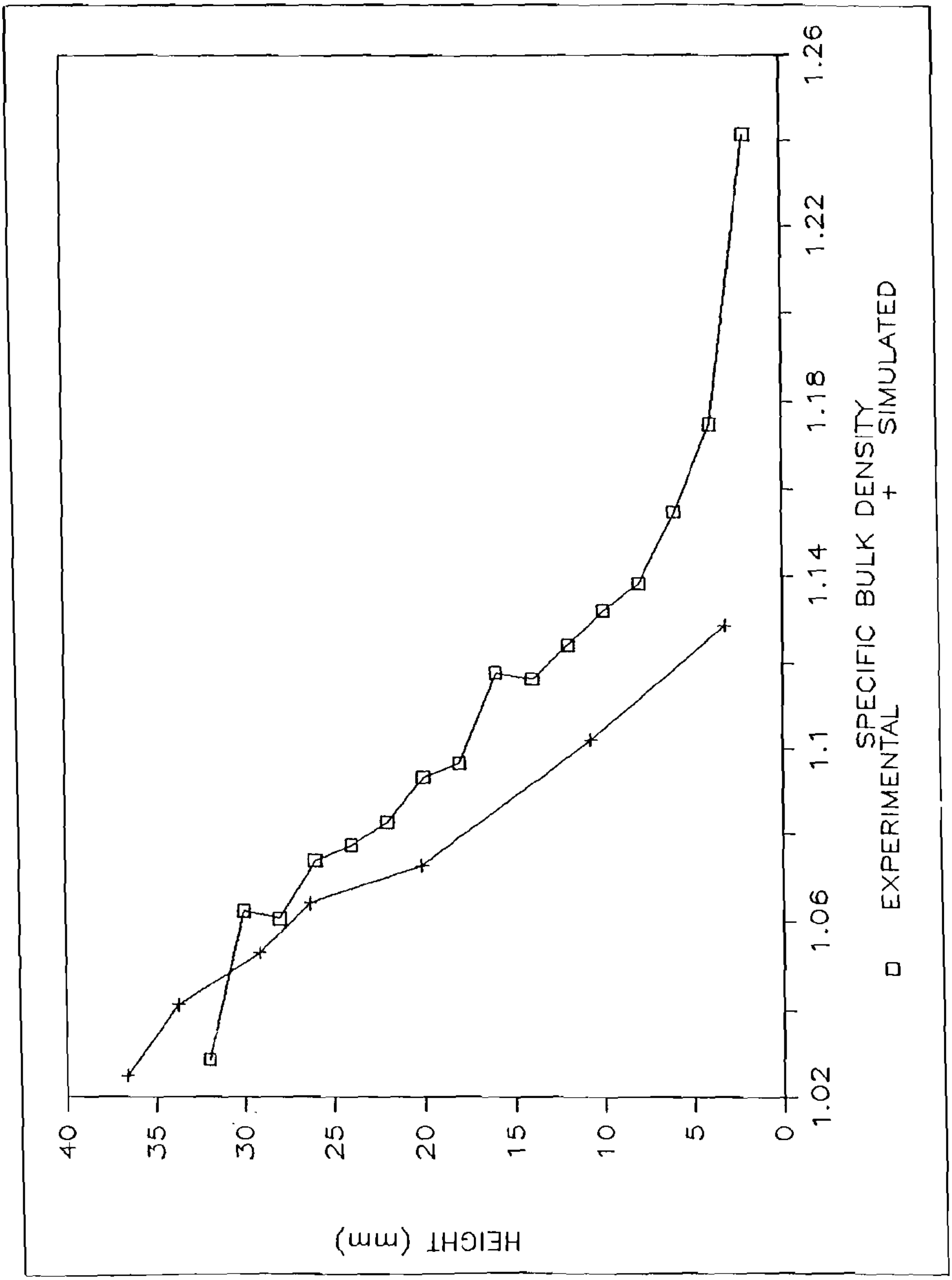



Fig 7A Test 7. Comparison of simulated and experimental bulk density profiles. Time = 24 hours

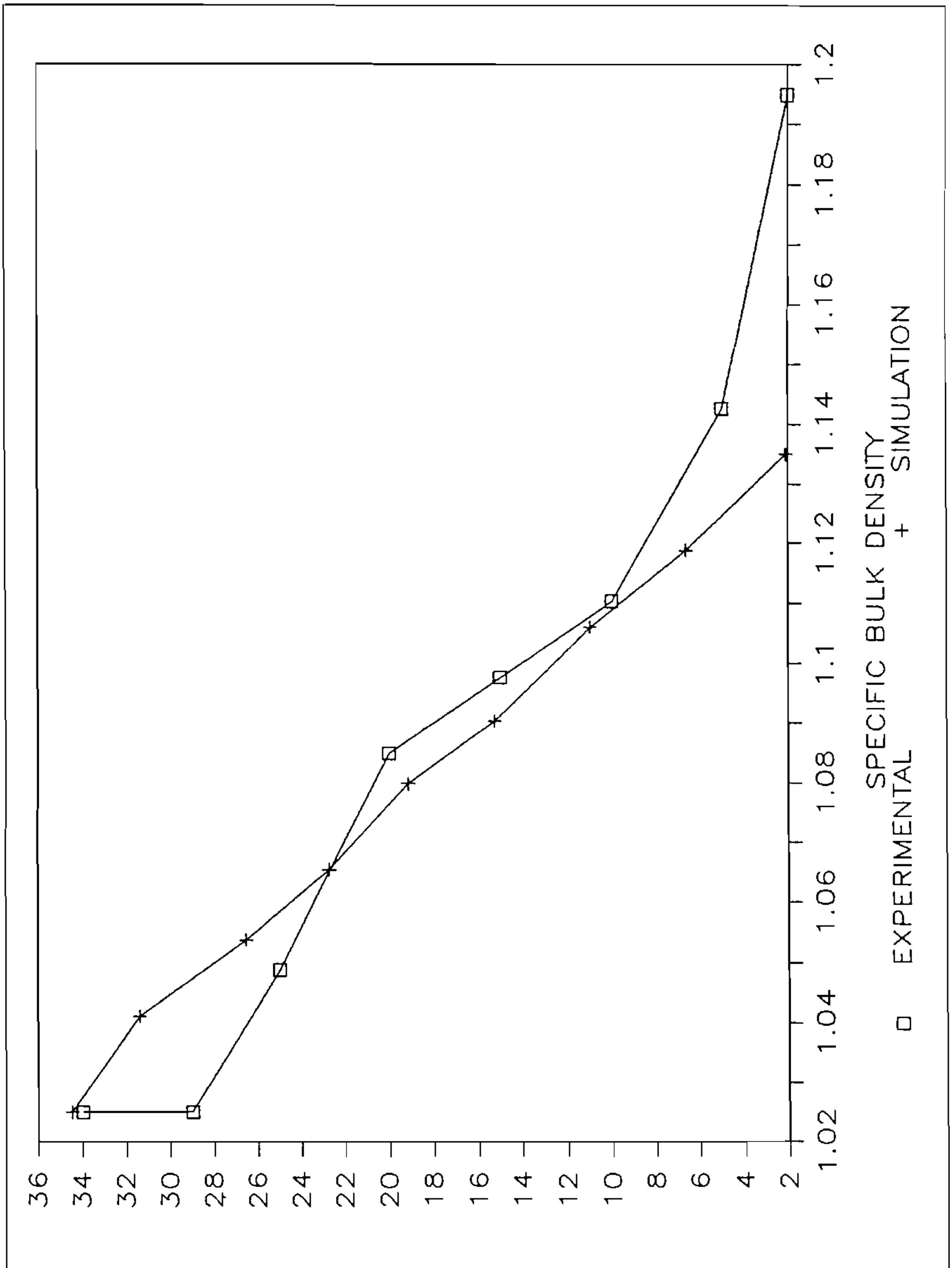



Fig 8A Test 8. Comparison of simulated and experimental bulk density profiles. Time = 24 hours

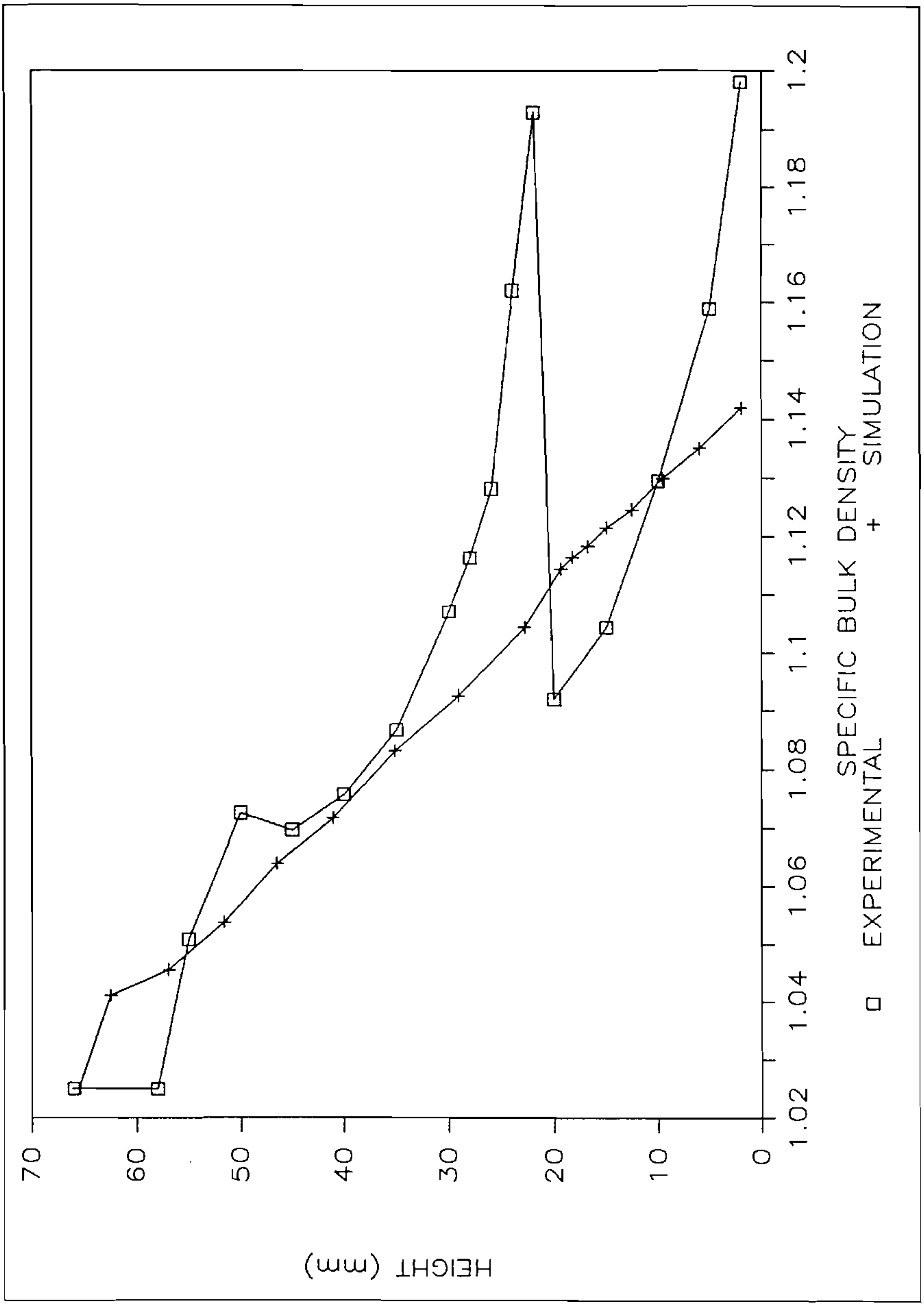



Fig 8B Test 8. Comparison of simulated and experimental bulk density profiles. Time = 48 hours

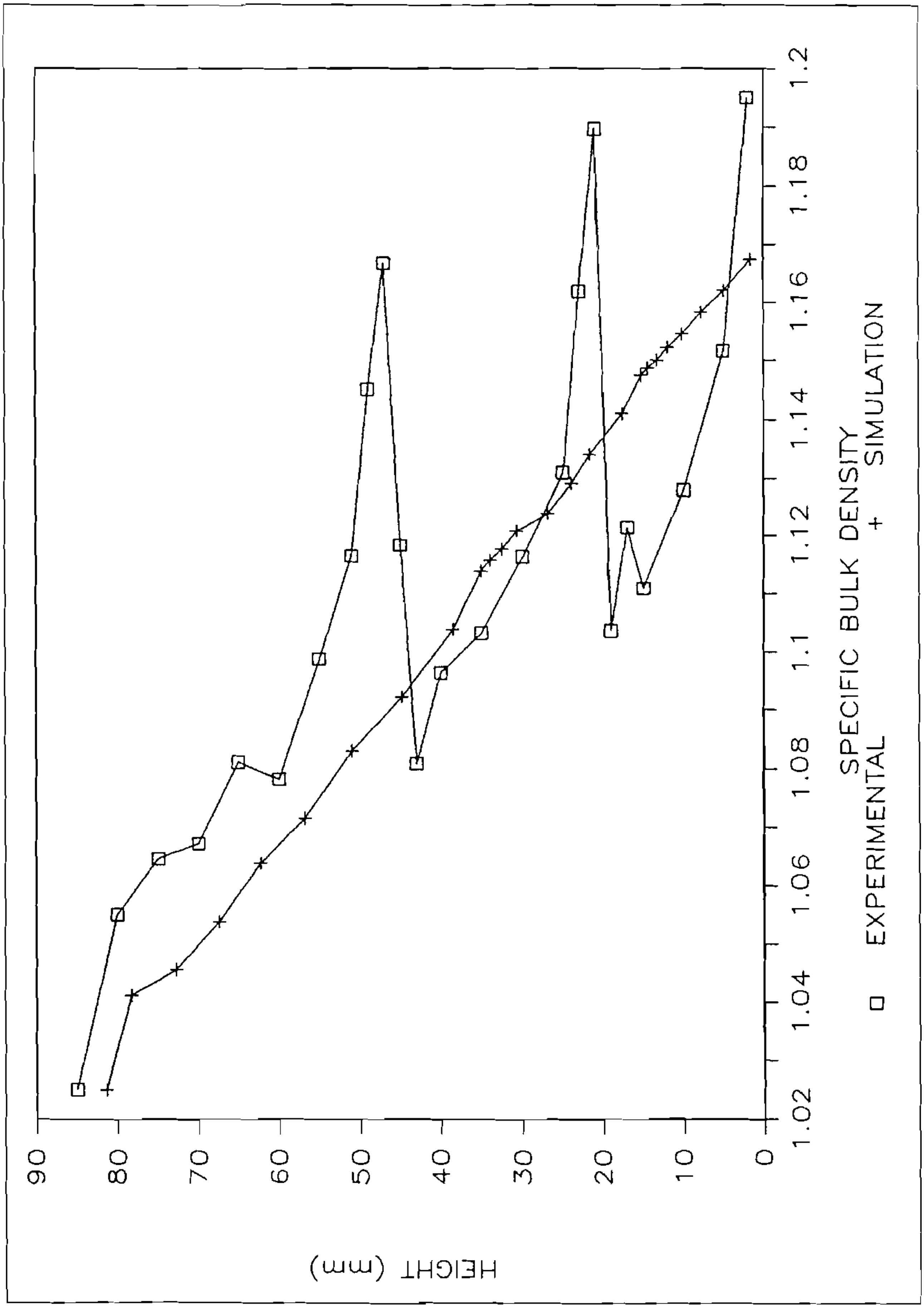



Fig 8C Test 8. Comparison of simulated and experimental bulk density profiles. Time = 72 hours

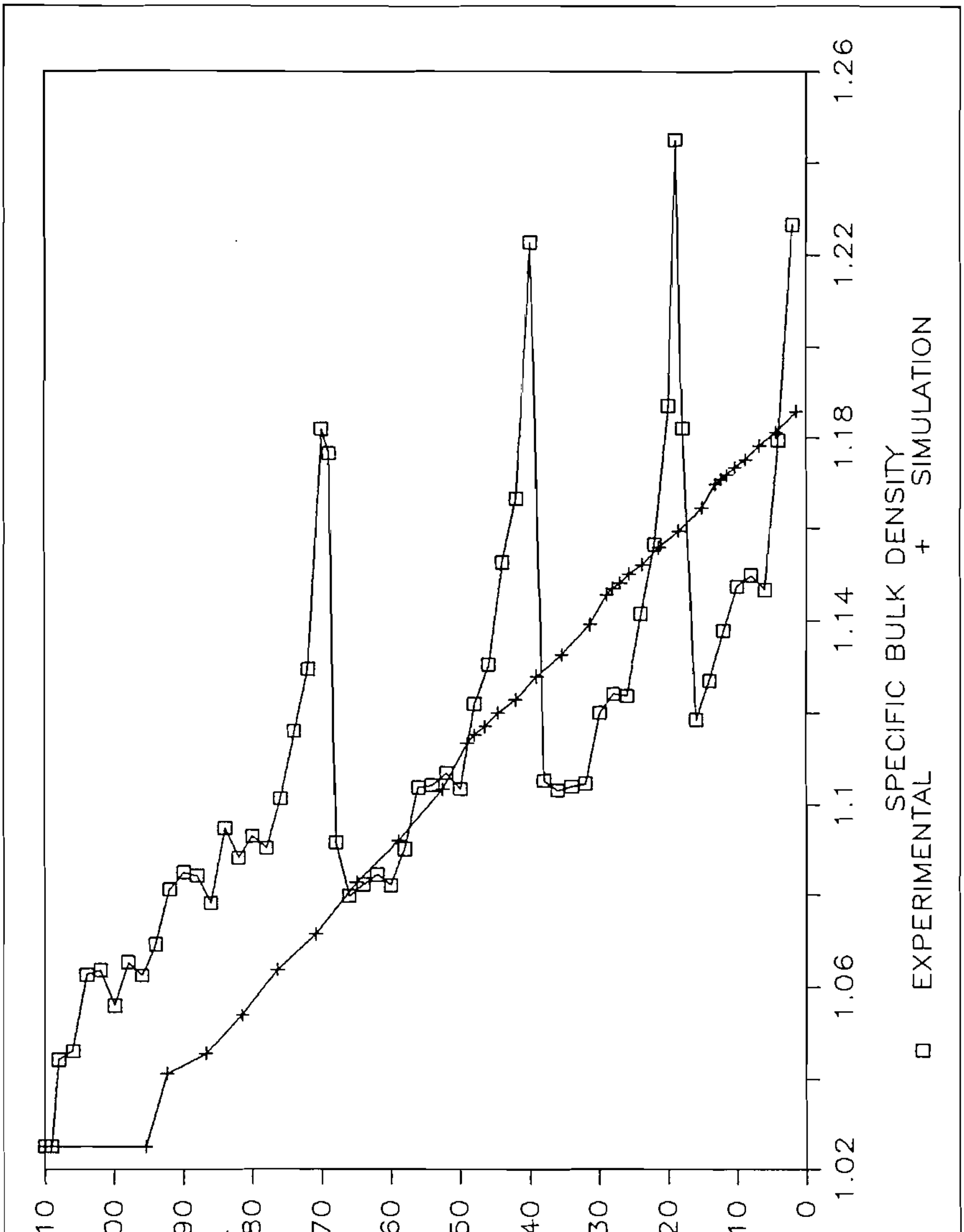



Fig 8D Test 8. Comparison of simulated and experimental bulk density profiles. Time = 98 hours

PLATES

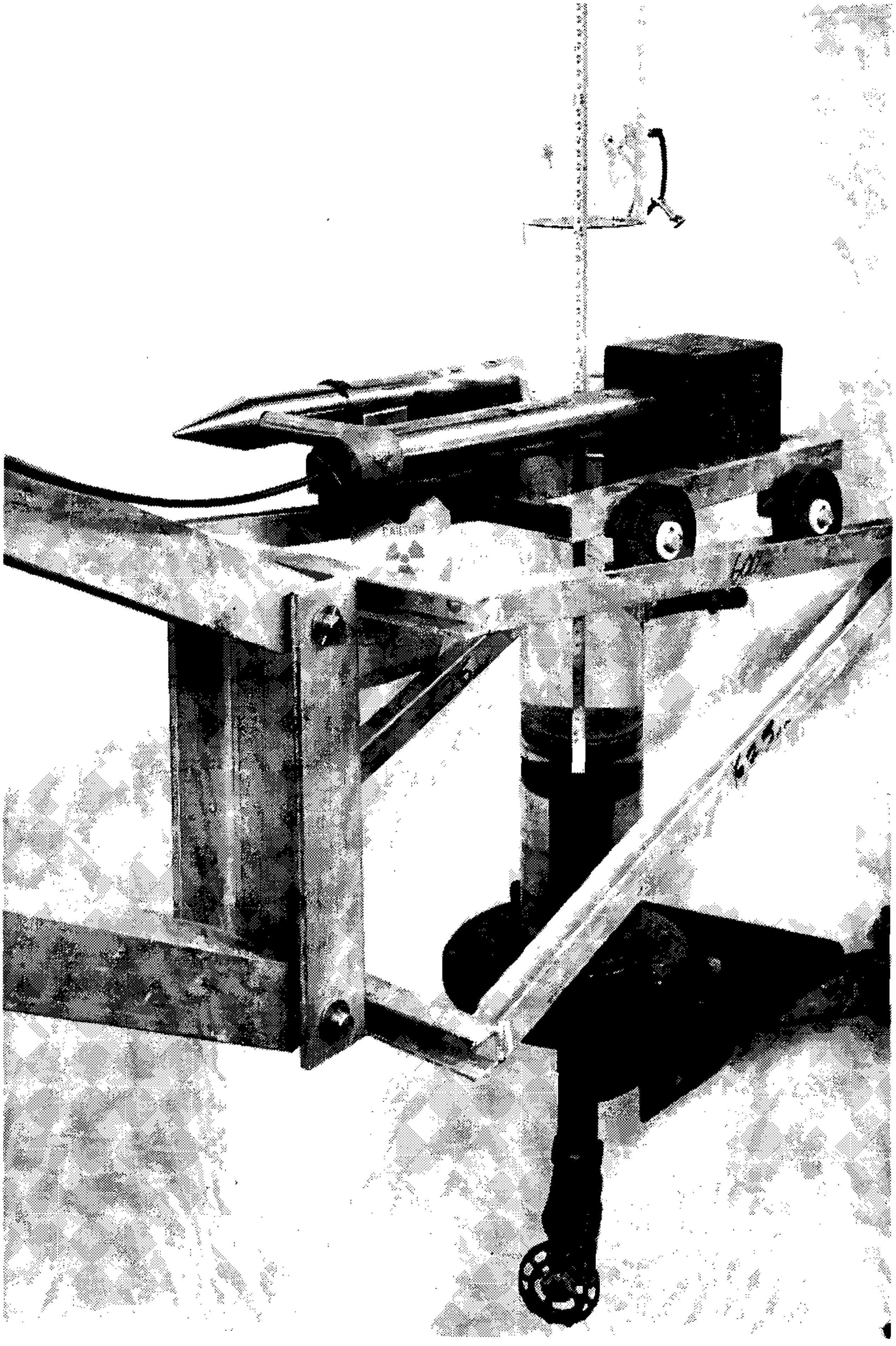
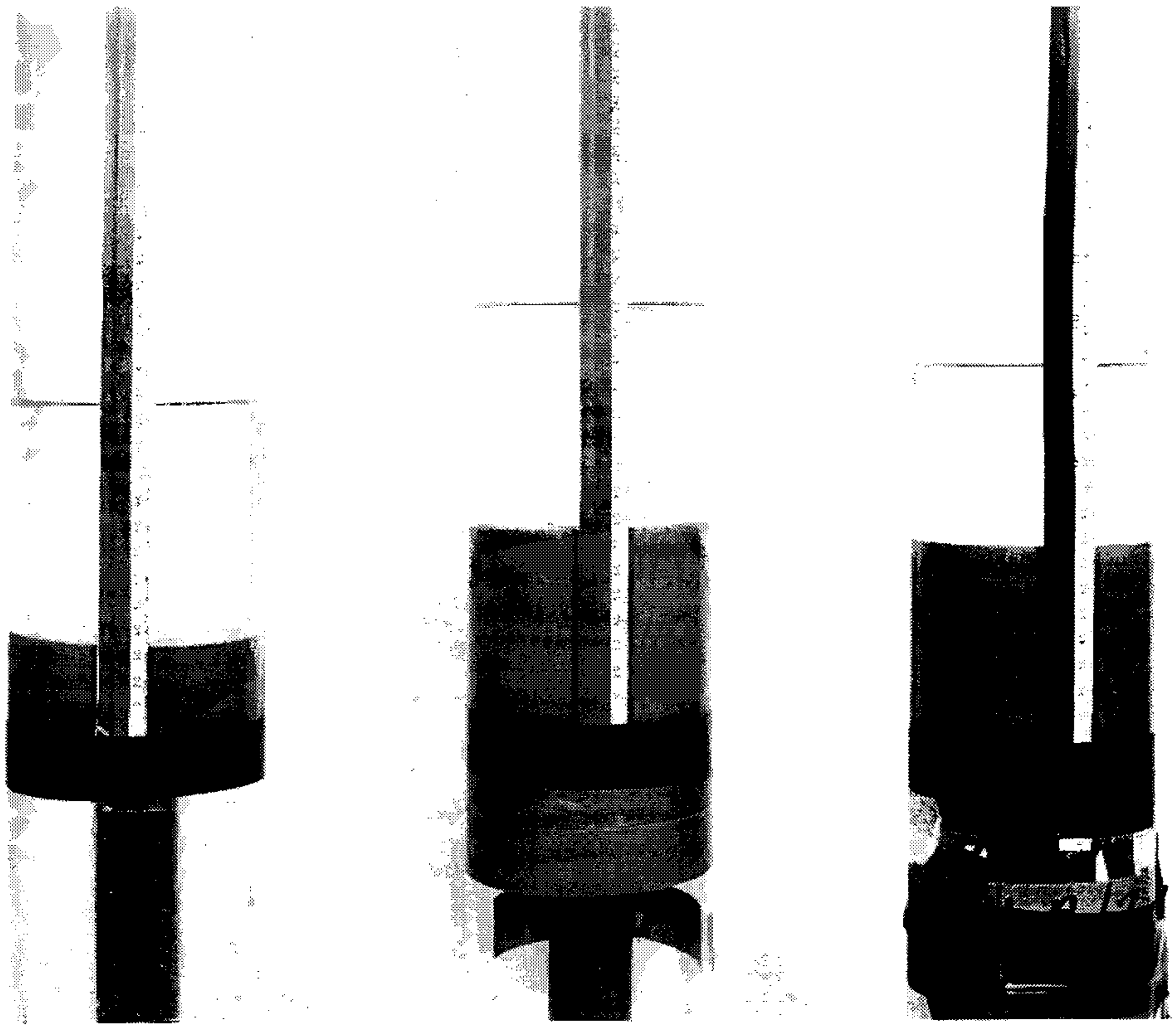
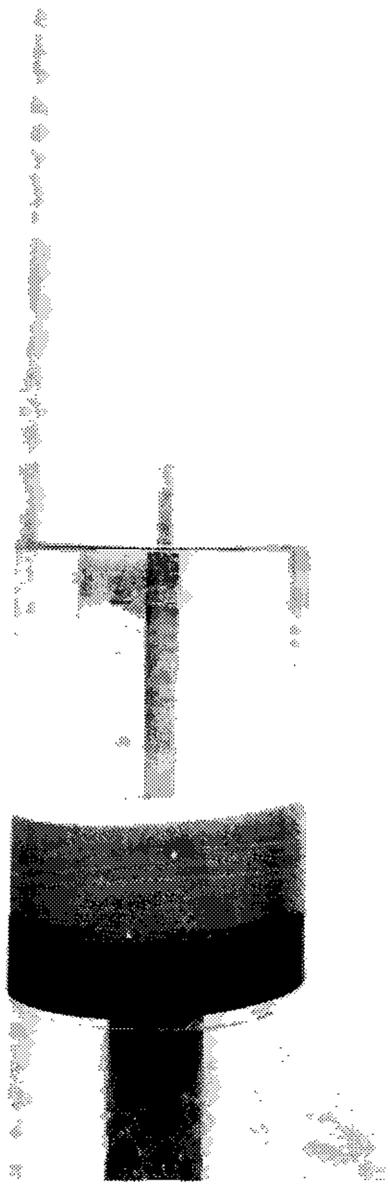


PLATE 1 Density measuring apparatus

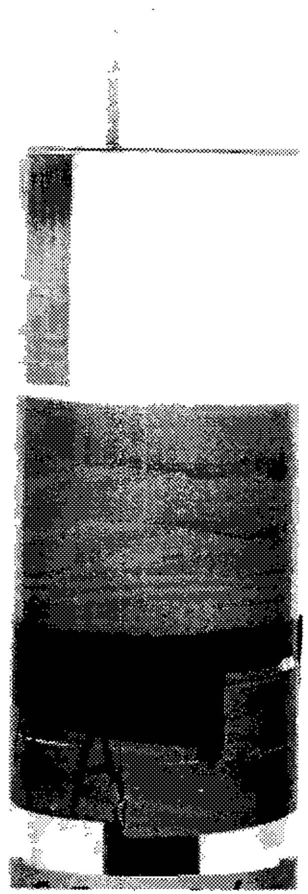


TEST 6 TEST 7 TEST 8

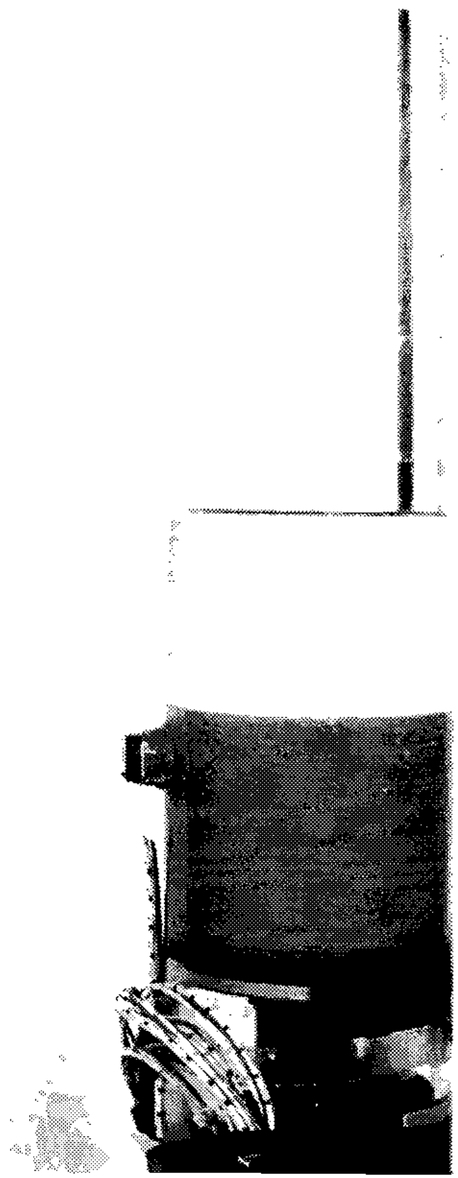
PLATE 2 Layering of mud deposits



TEST 6



TEST 7



TEST 8

PLATE 3 Non uniform thickness of experimental beds

# APPENDIX.

# APPENDIX A

## EXPERIMENTAL DETERMINATION OF A CONSOLIDATING MUD DEPOSIT

A P DISERENS BSC

## APPENDIX A: Experimental procedure

**A1.1 Description of apparatus**

The tests were carried out in a perspex settling column of 92mm internal diameter constructed of perspex sections so that the height could be varied from 1 to 4m as required (see Fig 5). A sampling port at 0.5m above the base of the column was used to enable small volumes of the suspension to be withdrawn for concentration and salinity analysis. The column was graduated in millimetres for the first half metre section and marked at 1 metre intervals throughout its length.

**A1.2 Density measurements**

Density profiles were obtained for each bed in the settling column by measuring the transmissance of emissions from a $^{133}Ba$ source, at 2mm intervals throughout the depth of the bed.

Accordingly, the density probe was calibrated by measuring the count rate in saline solutions of known density. This indicated a linear relationship over the density range applicable in the tests given by

$$\rho_b = -1.807\ 10^{-5}\ C_r + 2.357$$

in which

$\rho_b$ is bulk density $T/m^3$
$C_r$ is count rate per minute

Because the total quantity of sediment in the initial suspension 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.

**A1.3 Test procedure** The mud used throughout the experimental investigation was from Port Kelang (Malaysia). The mud was sieved through a 106μm sieve to remove shells, sand and large organic particles. A stock suspension was made up of around 20 g/l of mud at 33 g/l NaCl. This suspension was well mixed in a conical mixing tank.

The concentration of suspension put in the settling column at the start of each test were chosen to represent concentrations likely to be found in the field and were in the range 1,000 to 10,000mg/l.

In the first five tests the suspension was diluted to the required concentration with saline water and stirred manually prior to being poured into an empty column to the required depth (1 to 4m).

In the second series of tests the suspension was diluted to the required concentration and held in a container above the column. Before adding material, clear water above the bed was carefully drained off until the water level had fallen by lm. After stirring with a rotary stirrer, a portion of the suspension was added to the column from a tap until the depth had increased by lm. This process was repeated every 24 hours for 4 days.

For the first series of tests density profiles were obtained at approximately hourly intervals over the first five hours of each test. Further density profiles were determined at the end of each test. During the second series of tests the time interval for density profiles was decreased to 15 minutes to give a better estimate of deposition rate of the first layer. A profile was also obtained at 24 hourly intervals.

The count rate was measured over a 30 second time period at 2mm vertical intervals. A 20mm profile took 10 minutes to measure. The time quoted for each profile was the time midway through the measuring procedure.

The bed thickness was also recorded at the same time as the density profiles. There was a clear distinction in all tests between the suspension and the bed.

## A1.4 Series I: Single suspension

The first five experiments undertaken were to examine the effect of variation in the depth and suspended solids concentration of the initial water column on the rate and initial voids ratio of deposition.

**Test 1**

A suspension of 983mg/l mud in saline solution (approx 35g/l NaCl) was placed in a settling column to a depth of 2 metres,giving a total mass of $1930 g/m^2$. Bed thickness and density profiles were measured at various times during deposition and consolidation. The test was ended after 3 days.

**Test 2**

A suspension of approximately twice the concentration of that used in Test 1 (1900mg/l) was put in a column to a depth of 1 metre (giving approximately the same total mass as experiment 1). The column was monitored during deposition and consolidation as Test 1.

**Test 3**

A suspension of half the concentration of Test 1 was placed in a 4m settling column (giving approximately the same total mass of sediment as in Tests 1 and 2) and monitored similarly.

**Test 4**

This was a repeat of Test 1 to give an indication of the repeatability of the test results.

**Test 5**

The same height of column as Test 1 was used (2 metres) with twice the concentration of suspension (giving twice the total mass) and once again monitored for bed thickness and density profiles throughout deposition and consolidation.

<u>Series II Repeated consolidation</u>

The purpose of Tests 6 to 8 were to represent deposition and consolidation of a bed with a periodic deposition of sediment. The top metre of a 2m water column was replaced with a mud suspension of set concentration at time intervals of 24 hours from a stock suspension (see Fig 5). The density profile was measured before the addition of each new layer of sediment and during settlement and consolidation of the first bed.

**Test 6**

A stock suspension of approximately 1.3g/l was used giving around 1.3kg/$m^2$ of bed per day. The test was continued for four days.

**Test 7**

A stock suspension of approximately 4.2g/l was used giving 4.2kg/$m^2$ of bed per day. Density readings were not obtained after the first 24 hours. However the test was continued for 4 days, the mass of each layer was estimated from the suspension concentration.

**Test 8**

A stock suspension of approximately 3.6g/l was used giving 3.6kg/$m^2$ of bed per day. The test was continued for 5 days.

## A2 RESULTS OF EXPERIMENTS

**A2.1 Density readings** The variation in bed thickness with time and the density profile at successive times throughout each test were recorded. These two sets of results were used to calculate the variation in total mass and voids ratio with time for each test.

**A2.2 Calculation of deposition rate** The deposition rate (kg/$m^2$/day) over each 15 minute time interval was required as input to the computer model. This was found by calculating the dry density $\rho_d$ from the bulk density $\rho_b$ using the relation:

$$\text{Dry density } \rho_d = (\rho_b - \rho_w)/(1-1/sg) \qquad (1)$$

where $\rho_w$ = density of salt solution (1025 kg/$m^3$)
sg = specific density of sediment (2.65)

The dry densities were integrated over the height of the bed to give total mass at successive times throughout each test. A graph of total mass per $m^2$ with time was plotted during the deposition phase for each test. The increase in mass over each time period was read from the graph and from which the rate of deposition was calculated.

**A2.3 Calculation of initial voids ratio**

The mean voids ratio of the bed was calculated for each set of density measurements. The voids ratio (e) is given by:

$$e = \frac{V_v}{V_s} = \frac{V_t - V_s}{V_s} \qquad (2)$$

where $V_v$ = volume of voids
$V_s$ = volume of solids
$V_t$ = total volume

The initial voids ratio ($e_o$) was required as input to the computer simulation. A plot of the variation of the average voids ratio with time for each test was used to determine a realistic value of ($e_o$).

**A2.4 Checks on results**

The results of each series of tests are tabulated in Tables A3 and A4). The total mass in a bed was calculated by integrating the density profiles and may be compared with the total mass calculated from the initial concentration of suspension in the column for each test. The values for Tests 1 and 2 each agree to within 5%. However for Tests 3, 4, and 5 the difference is 30%, 20% and 13% respectively. This discrepancy in the figures is probably a combination of errors in the density readings (small errors in density readings result in large errors in total dry mass found by integration) or possibly the result of sampling errors.

**A2.5 Presentation of results**

The results of Tests 1 to 5 (Series 1) are given in Table A3. The variation of bed thickness, mass, and voids ratio with time are presented for each test (Figs A1-A5). The vertical density profiles at three times during each test have been plotted for each test (Figs A6-A10).

The results of Tests 6 to 8 (Series 2) are given in Table A4. For the Series 2 tests, graphs of the bed thickness, mass, and voids ratio against time were plotted for the first layer of deposition for Tests 6 to 8 (Figs A11-A13). The deposition rate for each layer and voids ratio during deposition were calculated.

Figures A11 to A13 show the Series 2 density profiles at 24 hour time intervals, except in Test 7 where density profiles were not obtained for days 2 to 4.

## A2.6 Discussion of results

### A2.6.1 Series 1 tests

Bed thickness was found to increase with time during an experiment until the rate of consolidation exceeded the rate of deposition after which the bed decreased in thickness (Figs A1 to A5).

The density profiles gave a uniform density with height during deposition but the lower layers of the bed increased in density faster than the upper layers during conslidation (Figs A6 to A10).

The total mass increased during the deposition phase and remained constant once deposition had ended, after approximately 5 hours (Fig A1 to A5).

The voids ratio decreased as the bed consolidated. Tests 1 and 3 gave initial voids ratios lower than the subsequent maximum value which was probably due to segregation during deposition giving lower voids ratio at the base of the bed.

The result for Test 4 gave a peak for total mass which subsequently decreased. This is obviously not correct as the mass of the bed should remain constant after deposition has ceased. However, this discrepancy was identified as being the result of a partial failure in the count recording instrument.

A2.6.2 Series 2

The Series 2 tests gave beds with visible layering; the layers being of the same mass but different thicknesses (ie different densities and voids ratios). Each layer had visible textural differences between the bottom and the top (see Plate 2). The very bottom of each layer consisted of a band of coarser material and organic particles. The layering was evident in the density profiles, the coarse material and organic matter giving a band of high density at the base of each layer (see Figs A14 to A16).

**A2.7 Experimentally accuracy**

The density profile was obtained by measuring the count rate over 30 secs at 2mm intervals vertically through the bed. The height was read with an accuracy of ±0.5mm and the time quoted for each profile was the average time for the density readings in that profile, since it took around 5 minutes to obtain readings for each 10mm of bed. The assumption was made that there was no significant change in density change over the time period taken to read the profile. There was a standard deviation for the density readings found in a previous investigation by Hydraulics Research of ±0.010kg/l. The natural decay of $^{133}Ba$ resulted in a very small change in the calibration of the density probe over a period of time but this was not significant in relation to the duration of the experiments.

The density probe gave consistent and acceptable readings, except for a temporary failure during Test 4. The erratic profiles obtained during deposition in each of the series I tests were considered to be the result of inhomogeneities in the bed which subsequently were not detectable after consolidation.

TABLE A1: SUMMARY OF SERIES 1 TESTS (TESTS 1 TO 5 )

| TEST No. | COLUMN HEIGHT (m) | INITIAL CONCENTRATION (g/l) | TOTAL MASS FROM SUSPENSION CONCENTRATION (Kg/m^2) | TOTAL MASS FROM DENSITY INTEGRATION (Kg/m^2) |
|---|---|---|---|---|
| 1 | 2 | 0.983 | 1.966 | 1.93 |
| 2 | 1 | 1.900 | 1.900 | 1.89 |
| 3 | 4 | 0.561 | 2.244 | 1.59 |
| 4 | 2 | 1.087 | 2.177 | 1.76 |
| 5 | 2 | 1.951 | 3.902 | 3.41 |

TABLE A2: SUMMARY OF SERIES 2 TESTS (TESTS 6 TO 8 )

| TEST No. | COLUMN HEIGHT (m) | INITIAL CONCENTRATION (g/l) | TOTAL MASS FROM SUSPENSION CONCENTRATION (Kg/m^2) | TOTAL MASS FROM DENSITY INTEGRATION (Kg/m^2) |
|---|---|---|---|---|
| 6 | 1 | 1.374 | 1.374 | 1.23 |
| 7 | 1 | 4.124 | 4.124 | 4.74 |
| 8 | 1 | 3.615 | 3.615 | 3.35 |

TABLE A3. SERIES 1 RESULTS.

TEST 1
INITIAL CONCENTRATION: 0.98 g/l
COLUMN HEIGHT : 2 m

| TIME (hours) | BED THICKNESS (mm) | CUMULATIVE MASS (Kg/m^2) | VOIDS RATIO e |
|---|---|---|---|
| 53.33 | 20.0 | 1.93 | 26 |
| 4.95 | 34.5 | 1.50 | 94 |
| 2.65 | 42.0 | 1.41 | 111 |
| 1.10 | 44.0 | 0.95 | 174 |
| 0.98 | 28.0 | 0.48 | 219 |
| 0.68 | 17.0 | 0.44 | 137 |
| 0 | 0 | 0.00 | |

TEST 4
INITIAL CONCENTRATION: 1.08 g/l
COLUMN HEIGHT : 2 m

| TIME (hours) | BED THICKNESS (mm) | CUMULATIVE MASS (Kg/m^2) | VOIDS RATIO e |
|---|---|---|---|
| 70.00 | 17.0 | 1.76 | 25 |
| 5.83 | 27.5 | 1.75 | 41 |
| 4.76 | 29.5 | 1.86 | 41 |
| 2.88 | 35.0 | 2.42 | 37 |
| 2.40 | 37.0 | 2.55 | 37 |
| 1.81 | 34.5 | 2.18 | 41 |
| 1.44 | 27.0 | 1.66 | 42 |
| 1.06 | 16.0 | 0.90 | 46 |
| 0.87 | 10.0 | 0.56 | 46 |
| 0.68 | 5.0 | 0.22 | 59 |
| 0 | 0.0 | 0.00 | |

TEST 2
INITIAL CONCENTRATION: 1.90 g/I
COLUMN HEIGHT : 1 m

| TIME (hours) | BED THICKNESS (mm) | CUMULATIVE MASS (Kg/m^2) | VOIDS RATIO e |
|---|---|---|---|
| 72.00 | 19.5 | 1.89 | 27 |
| 4.92 | 29.0 | 1.91 | 41 |
| 3.90 | 34.5 | 1.81 | 49 |
| 2.01 | 41.0 | 1.67 | 66 |
| 1.32 | 48.5 | 1.44 | 88 |
| 0.86 | 39.5 | 1.04 | 101 |
| 0.33 | 5.5 | 0.12 | 130 |
| 0 | 0 | 0 | |

TEST 5
INITIAL CONCENTRATION: 1.95 g/l
COLUMN HEIGHT : 2 m

| TIME (hours) | BED THICKNESS (mm) | CUMULATIVE MASS (Kg/m^2) | VOIDS RATIO e |
|---|---|---|---|
| 71.98 | 29 | 3.413 | 22 |
| 23.00 | 37 | 3.199 | 30 |
| 6.60 | 57 | 3.132 | 47 |
| 4.23 | 65 | 2.914 | 58 |
| 1.89 | 92 | 2.767 | 87 |
| 1.23 | 75 | 1.677 | 117 |
| 0.73 | 37 | 0.861 | 113 |
| 0.44 | 16 | 0.322 | 131 |
| 0 | 0 | 0.000 | |

TEST 3
INITIAL CONCENTRATION: 0.56 g/l
COLUMN HEIGHT : 4 m

| TIME (hours) | BED THICKNESS (mm) | CUMULATIVE MASS (Kg/m^2) | VOIDS RATIO e |
|---|---|---|---|
| 56.67 | 16.0 | 1.597 | 25.544 |
| 6.13 | 20.5 | 1.495 | 35.346 |
| 5.29 | 22.5 | 1.200 | 48.687 |
| 4.29 | 22.5 | 1.062 | 55.136 |
| 3.80 | 22.5 | 1.071 | 54.668 |
| 2.92 | 17.5 | 0.721 | 63.295 |
| 2.58 | 14.5 | 0.557 | 67.958 |
| 2.22 | 10.0 | 0.511 | 63.846 |
| 1.87 | 7.5 | 0.320 | 61.070 |
| 1.57 | 5.0 | 0.279 | 46.410 |
| 0.00 | 0 | 0.000 | |

TABLE A4. SERIES 2 RESULTS.

TEST 6
CONCENTRATION : 1.37 g/l
(Added at 24 hour intervals)
COLUMN HEIGHT : 2 m

| TIME (hours) | BED THICKNESS (mm) | CUMULATIVE MASS (Kg/m^2) | VOIDS RATIO e |
|---|---|---|---|
| 168 | 40 | 5.14 | 19.61 |
| 72 | 33 | 4.39 | 18.90 |
| 48 | 23 | 2.75 | 21.16 |
| 24 | 12.5 | 1.23 | 26.00 |
| 4 | 19.5 | 1.23 | 34.63 |
| 3 | 22 | 1.21 | 47.18 |
| 2 | 21 | 1.10 | 49.52 |
| 1 | 8 | 0.24 | 85.81 |
| 0 | 0 | 0.00 | |

TEST 7
CONCENTRATION : 0.98 g/l
(Added at 24 hour intervals)
COLUMN HEIGHT : 2 m

| TIME (hours) | BED THICKNESS (mm) | CUMULATIVE MASS (Kg/m^2) | VOIDS RATIO e |
|---|---|---|---|
| 96 | 112 | 19.00 | 14.6 |
| 72 | 85 | 14.25 | 14.8 |
| 48 | 60 | 9.50 | 15.7 |
| 24 | 32 | 4.74 | 16.9 |
| 3 | 60 | 4.74 | 32.6 |
| 1.5 | 80 | 3.59 | 58.1 |
| 0 | 0 | 0.00 | |

TEST 8
CONCENTRATION : 3.60g/l
(Added at 24 hour intervals)
COLUMN HEIGHT : 2 m

| TIME (hours) | BED THICKNESS (mm) | CUMULATIVE MASS (Kg/m^2) | VOIDS RATIO e |
|---|---|---|---|
| 98 | 108 | 15.32 | 17.7 |
| 72 | 85 | 10.81 | 19.8 |
| 48 | 58 | 7.25 | 20.2 |
| 24 | 29 | 3.35 | 22.0 |
| 5.5 | 50 | 3.17 | 40.7 |
| 3 | 65 | 3.05 | 55.5 |
| 2 | 72 | 2.39 | 78.8 |
| 1.75 | 70 | 2.25 | 70.0 |
| 1.5 | 58 | 2.17 | 69.7 |
| 1.25 | 40 | 1.94 | 53.6 |
| 1 | 29 | 1.52 | 49.7 |
| 0.75 | 15 | 1.36 | 28.2 |
| 0.5 | 5 | 0.91 | 13.6 |
| 0 | 0 | 0.00 | 16.4 |

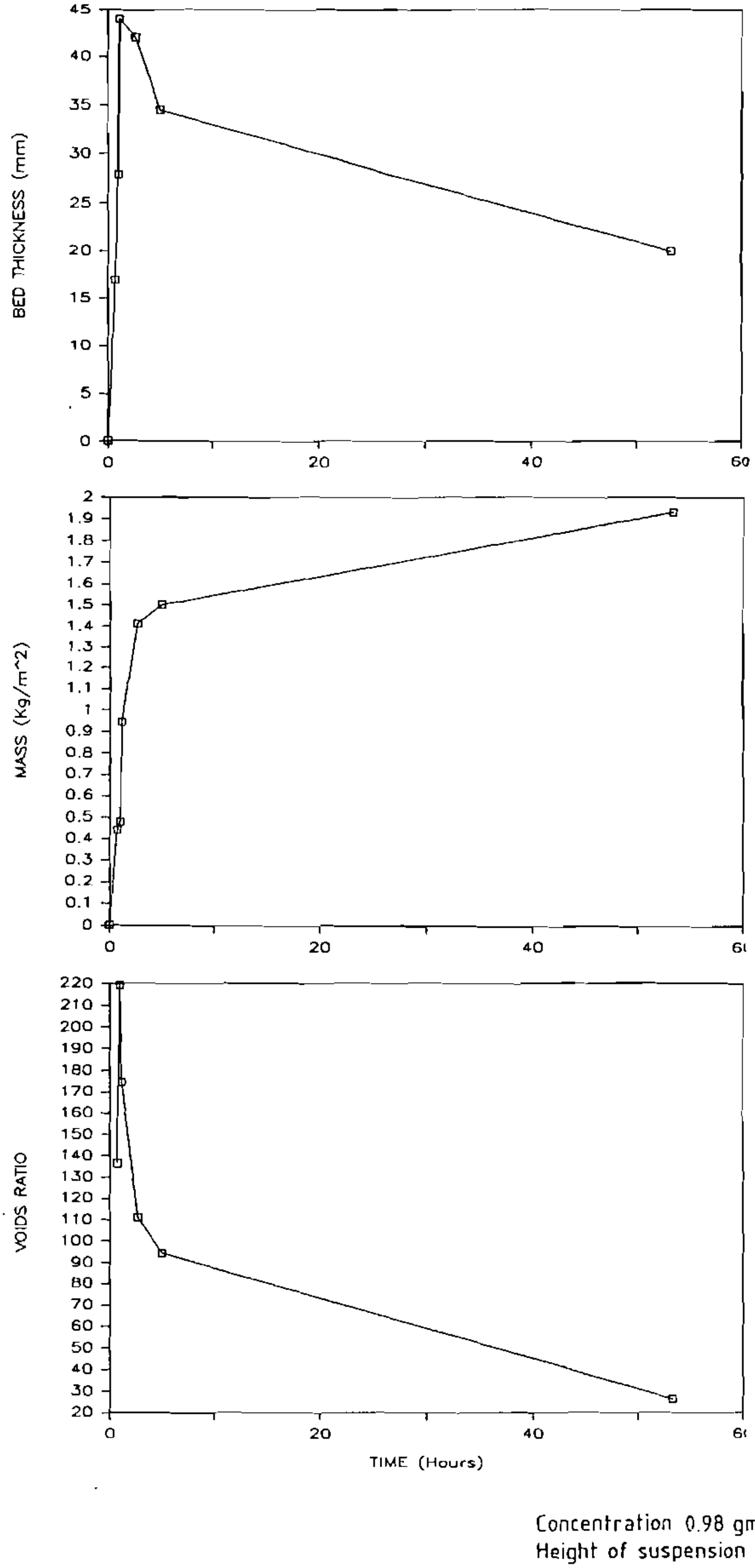



Fig A1 Test No.1. Variation of bed thickness, mass and voids ratio with time

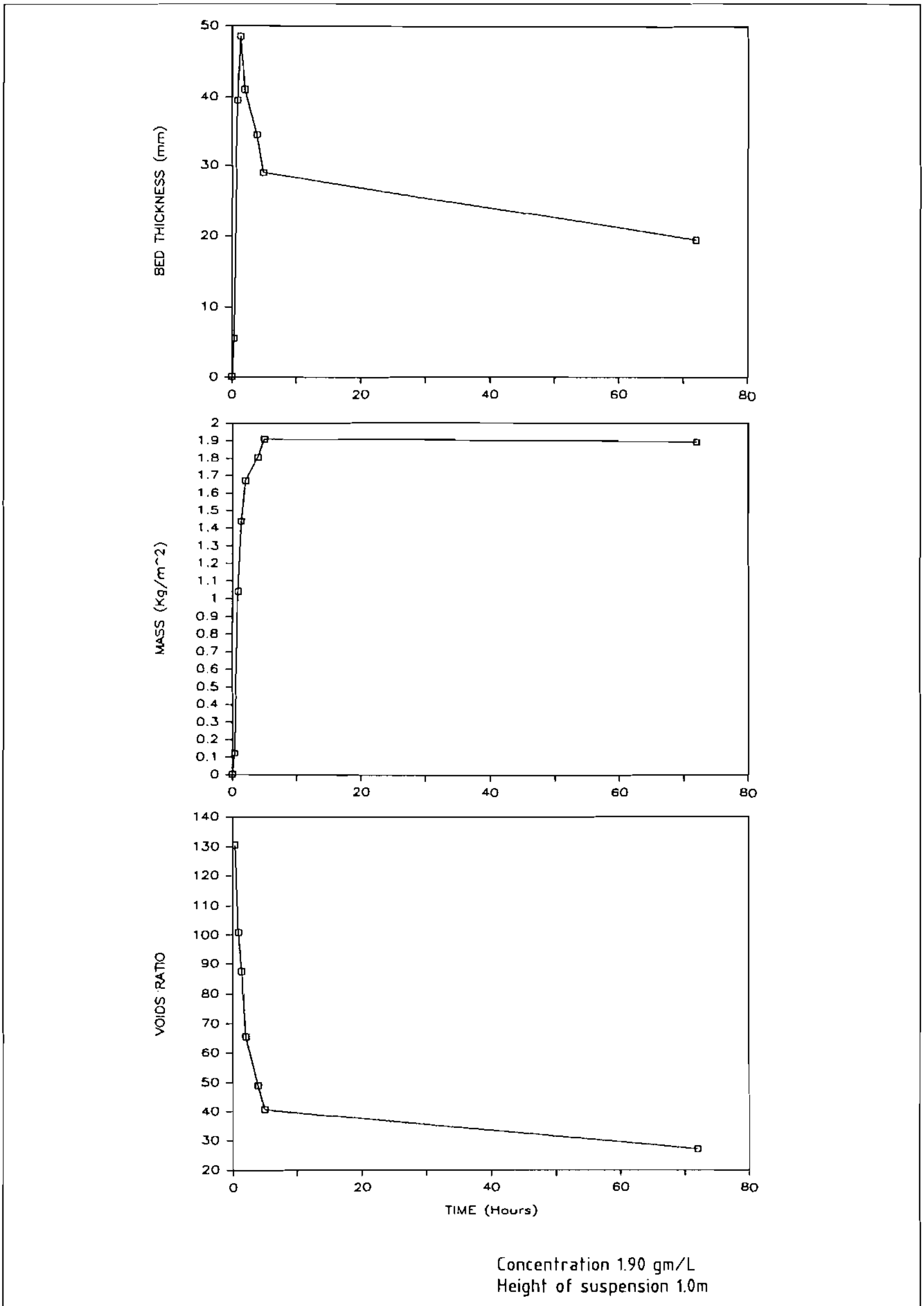



Fig A2  Test No.2. Variation of bed thickness, mass and voids ratio with time

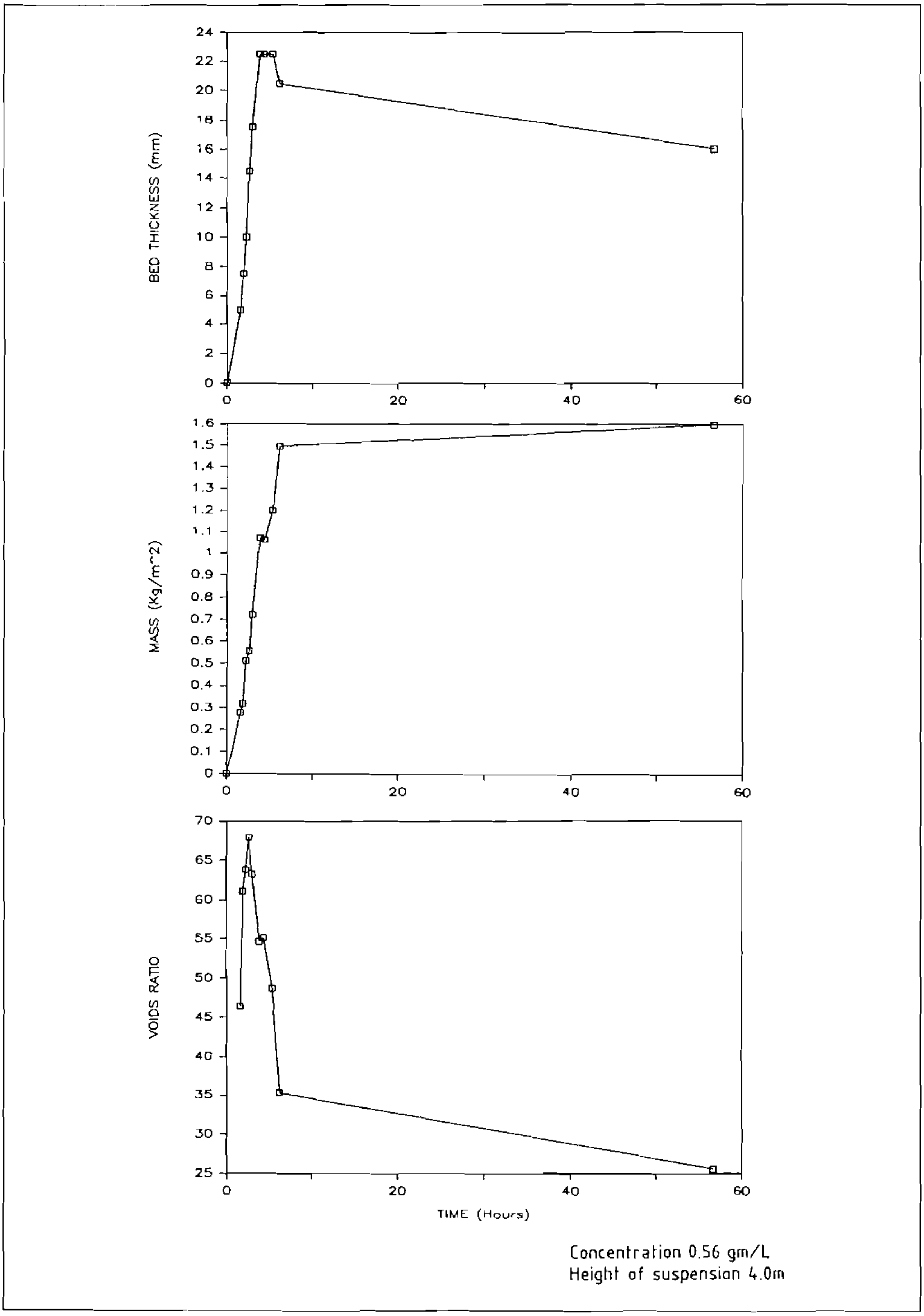



Fig A3 Test No.3. Variations of bed thickness, mass and voids ratio with time

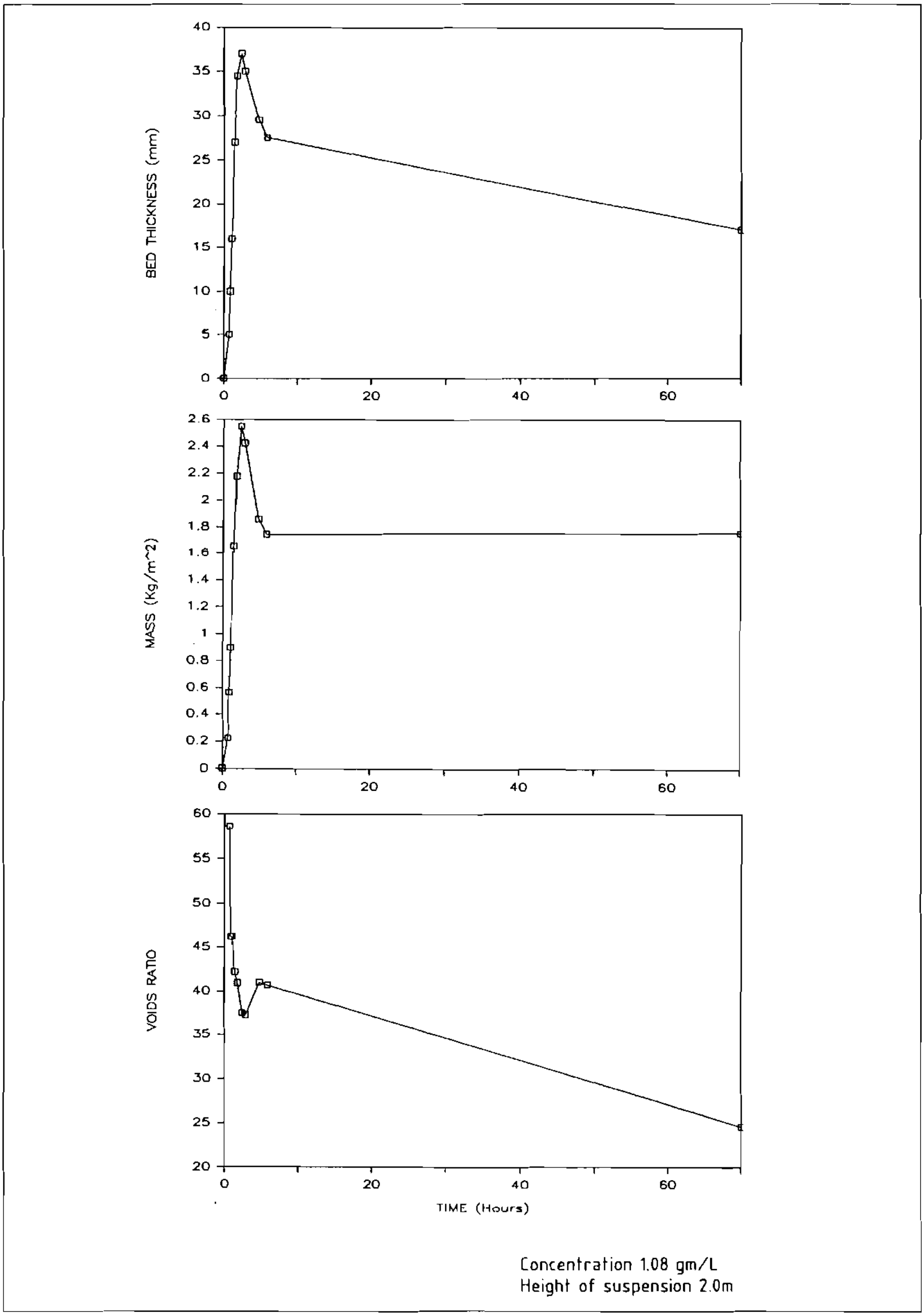



Fig A4 Test No.4. Variation of bed thickness, mass and voids ratio with time

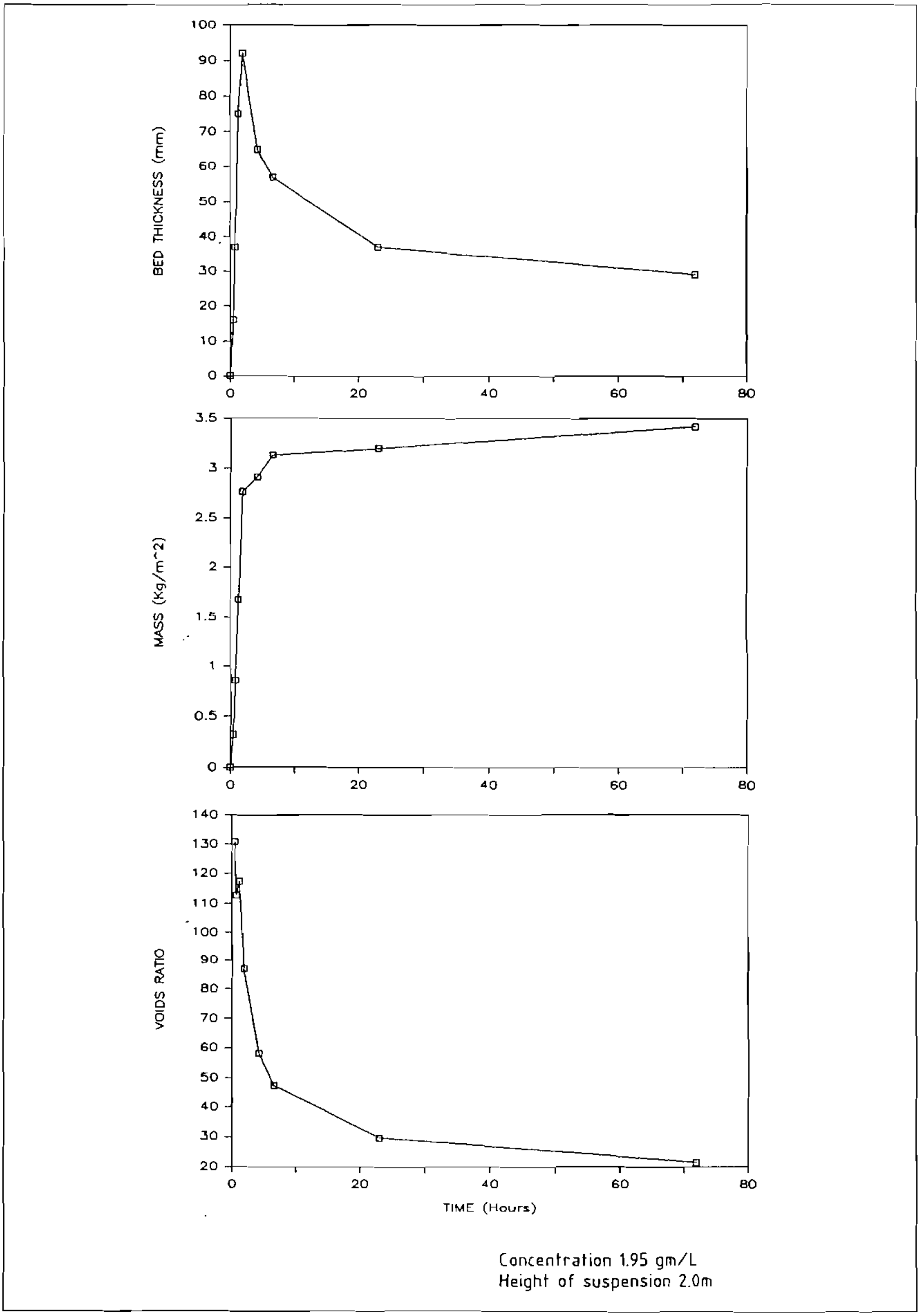



Fig A5 Test No.5. Variation of bed thickness, mass and voids ratio with time

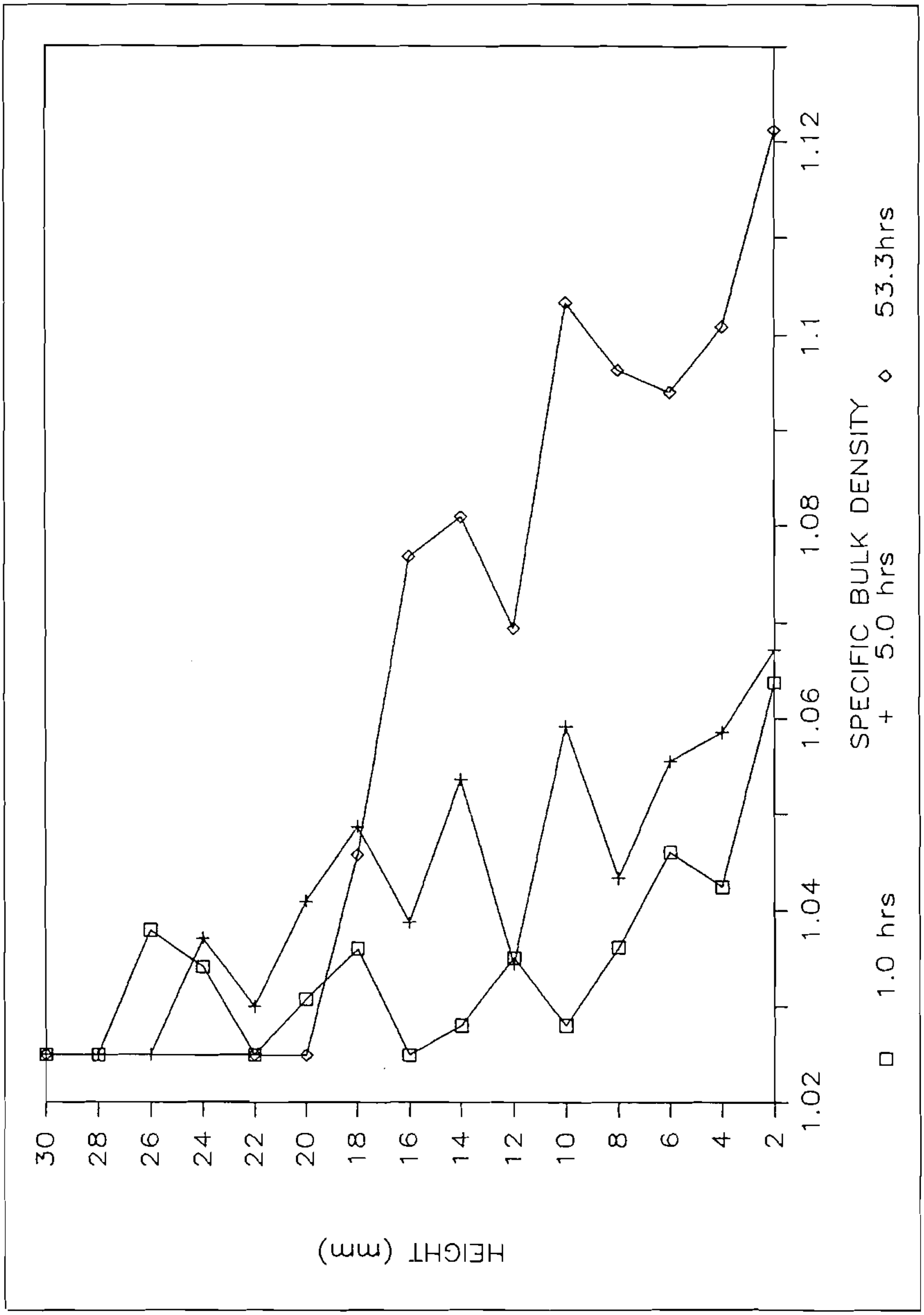



Fig A6 Test 1. Experimental density profiles

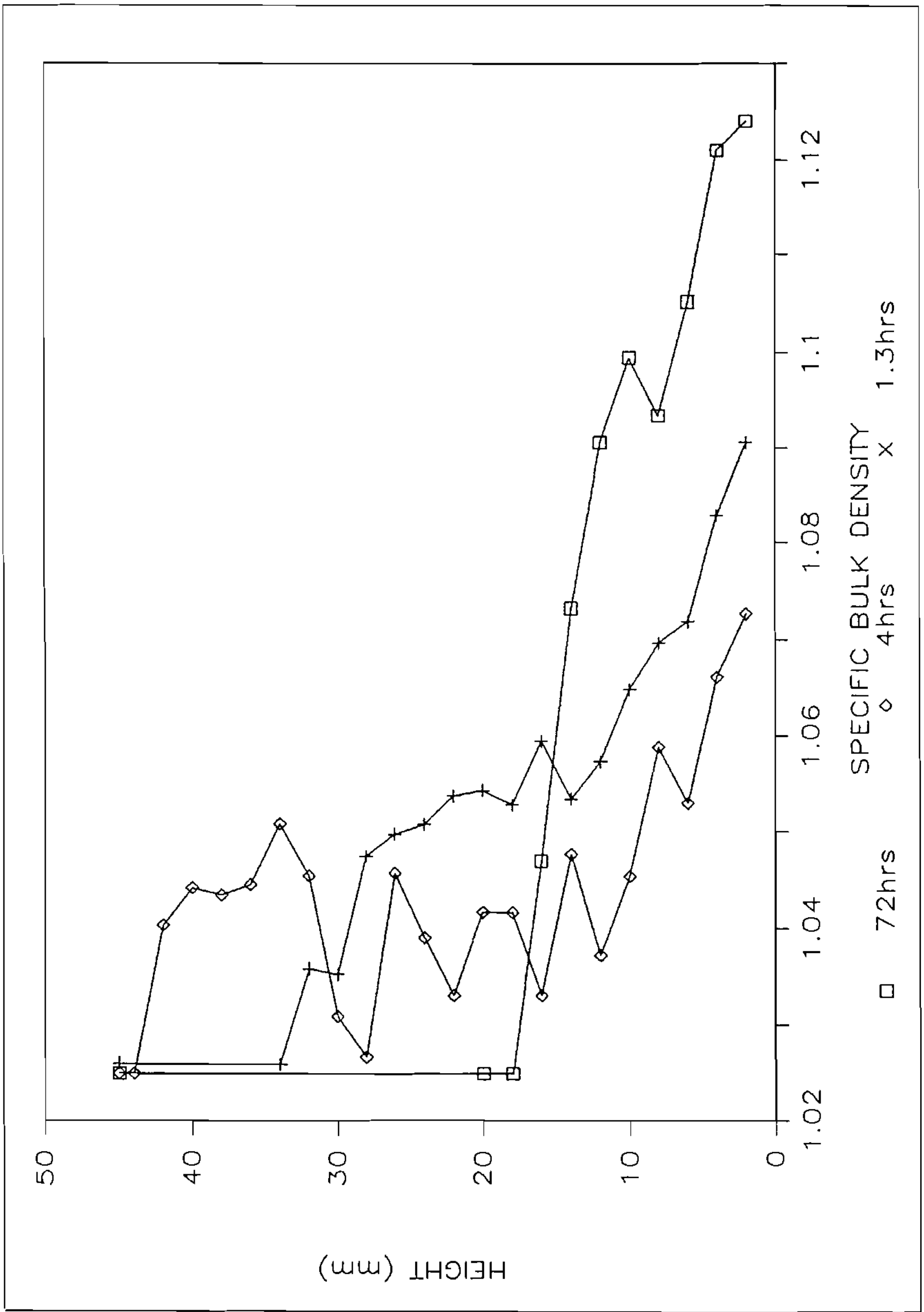



Fig A7 Test 2. Experimental density profiles

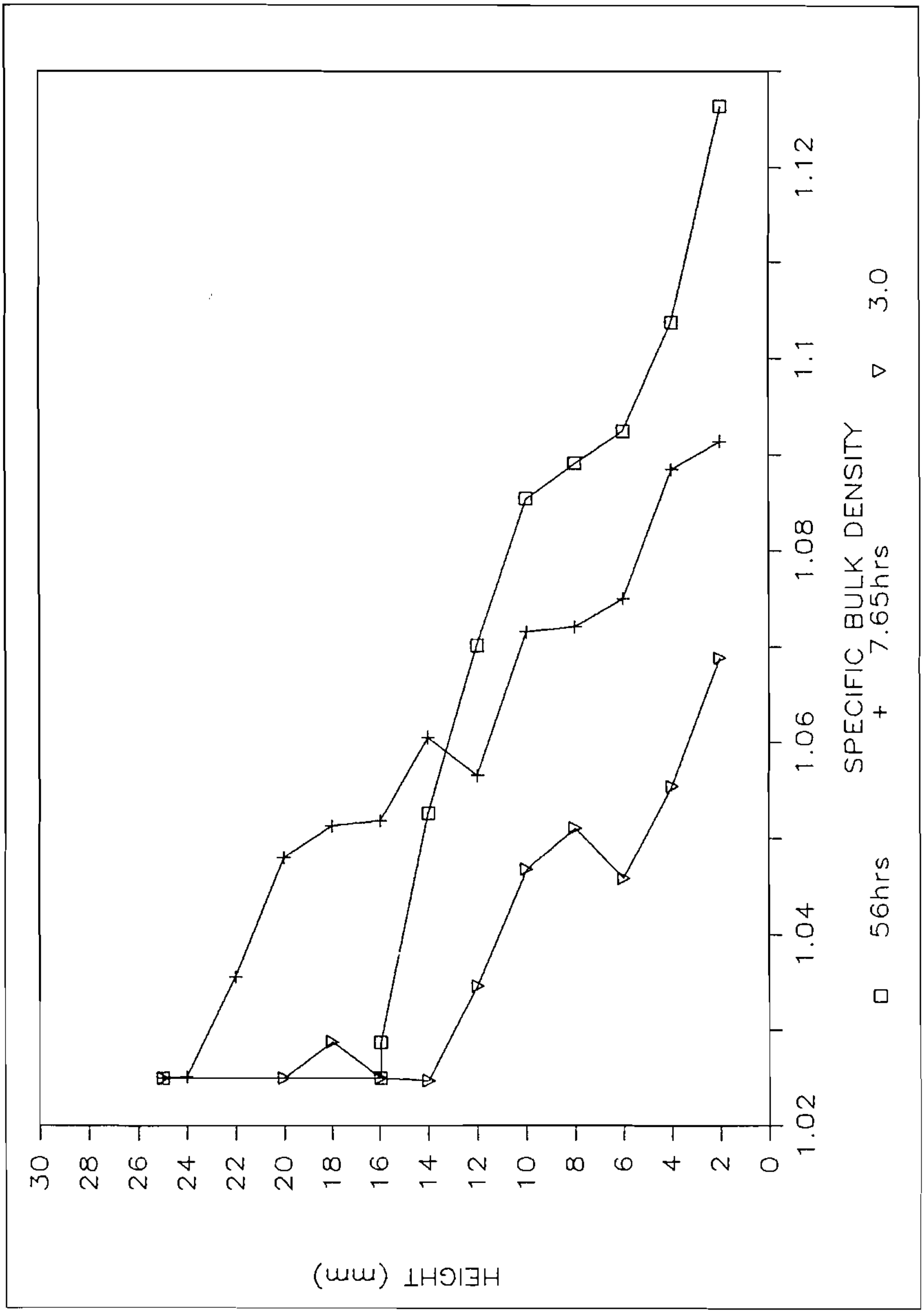



Fig A8 Test 3. Experimental density profiles

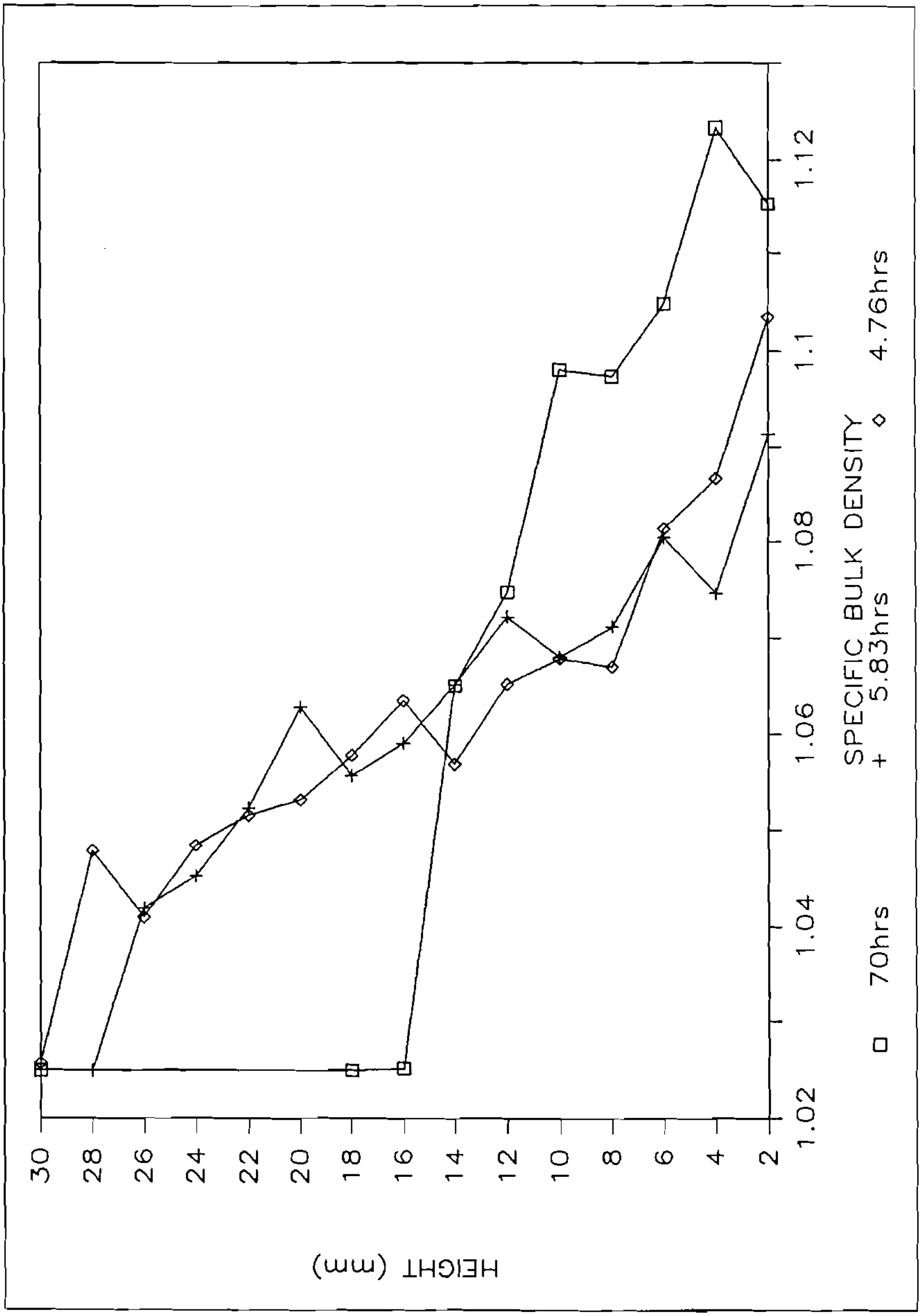



Fig A9 Test 4. Experimental density profiles

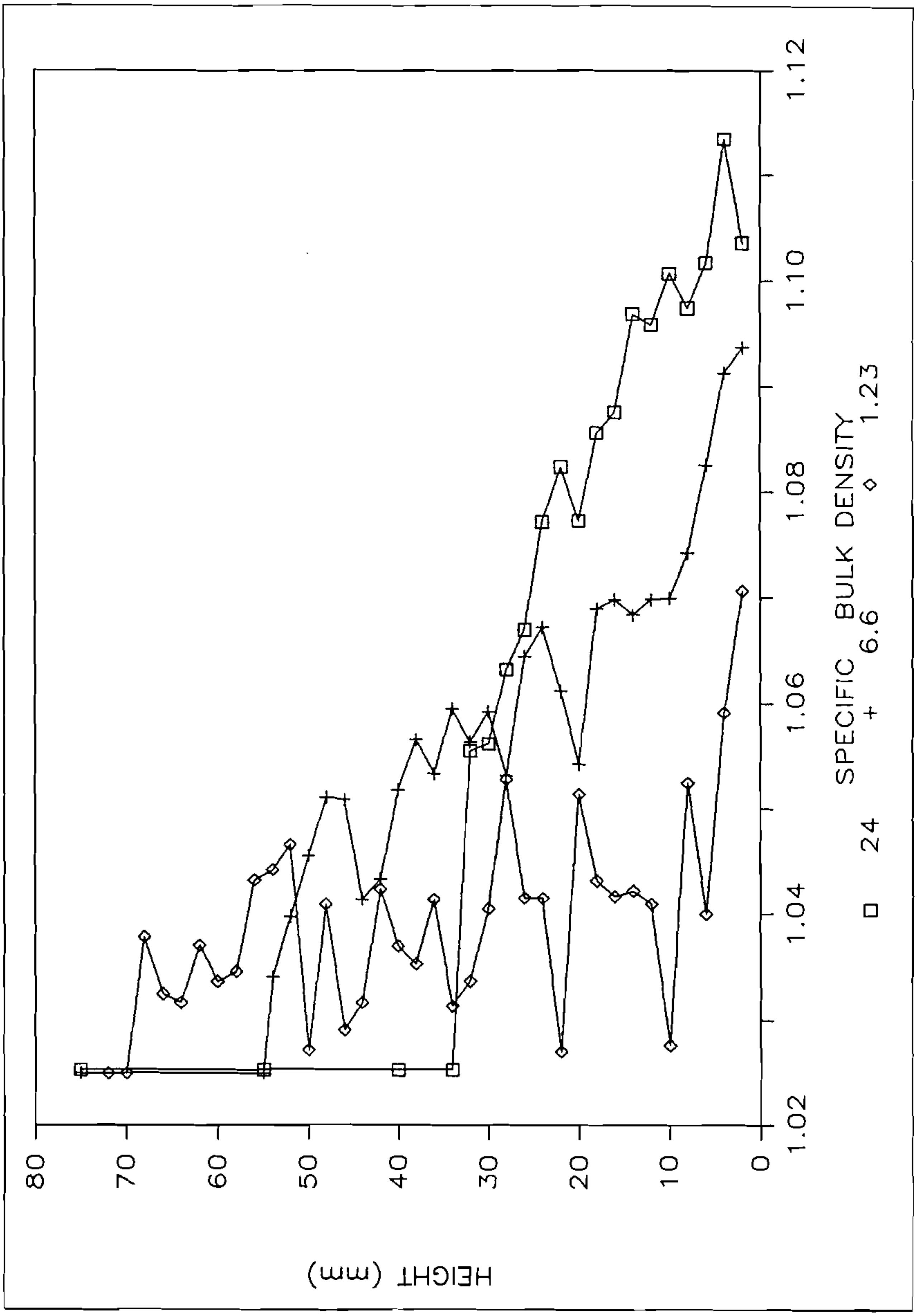



Fig A10 Test 5. Experimental density profiles

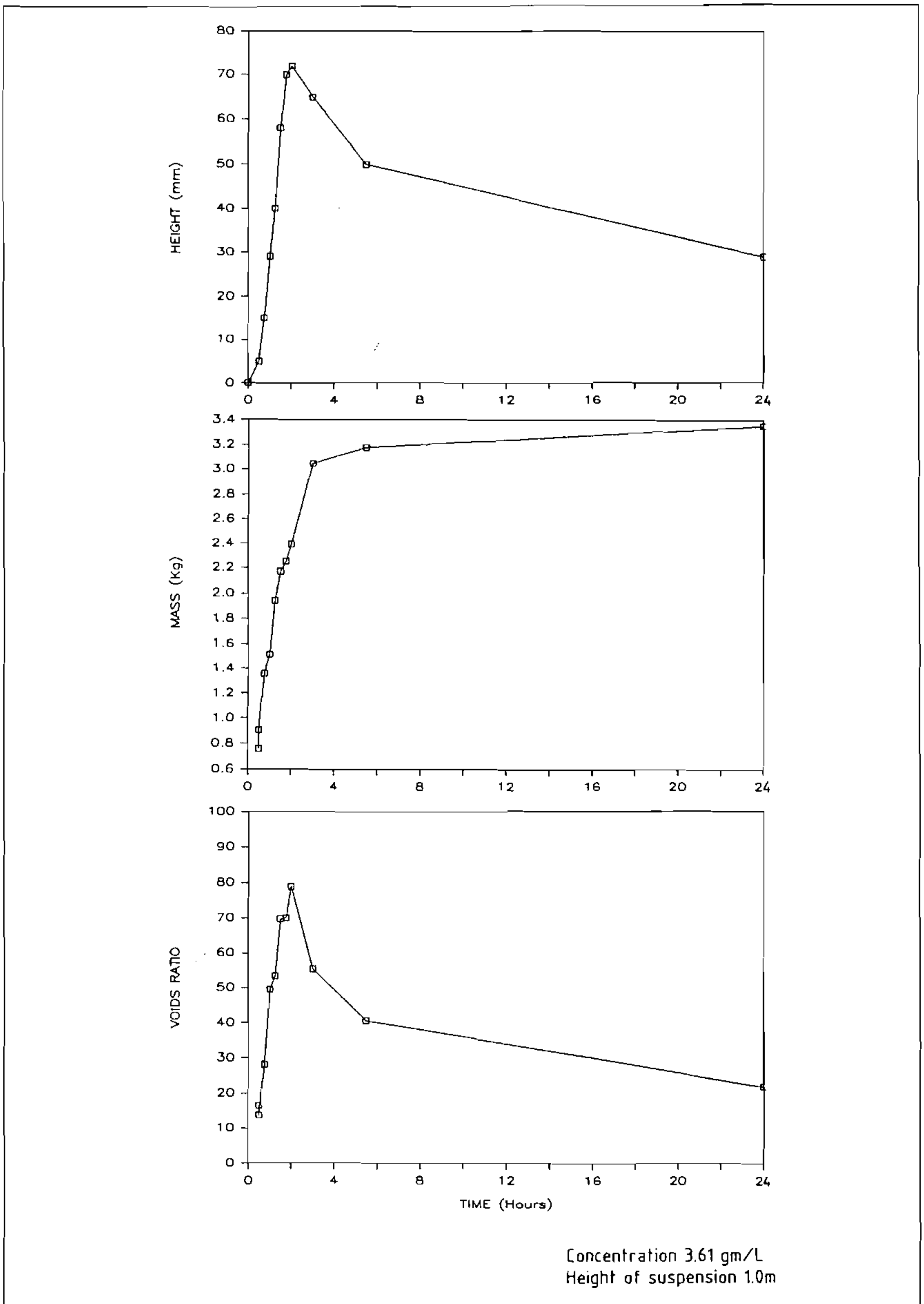



Fig A13 Test No.8. Variations of bed thickness, mass and voids ratio with time for first layer

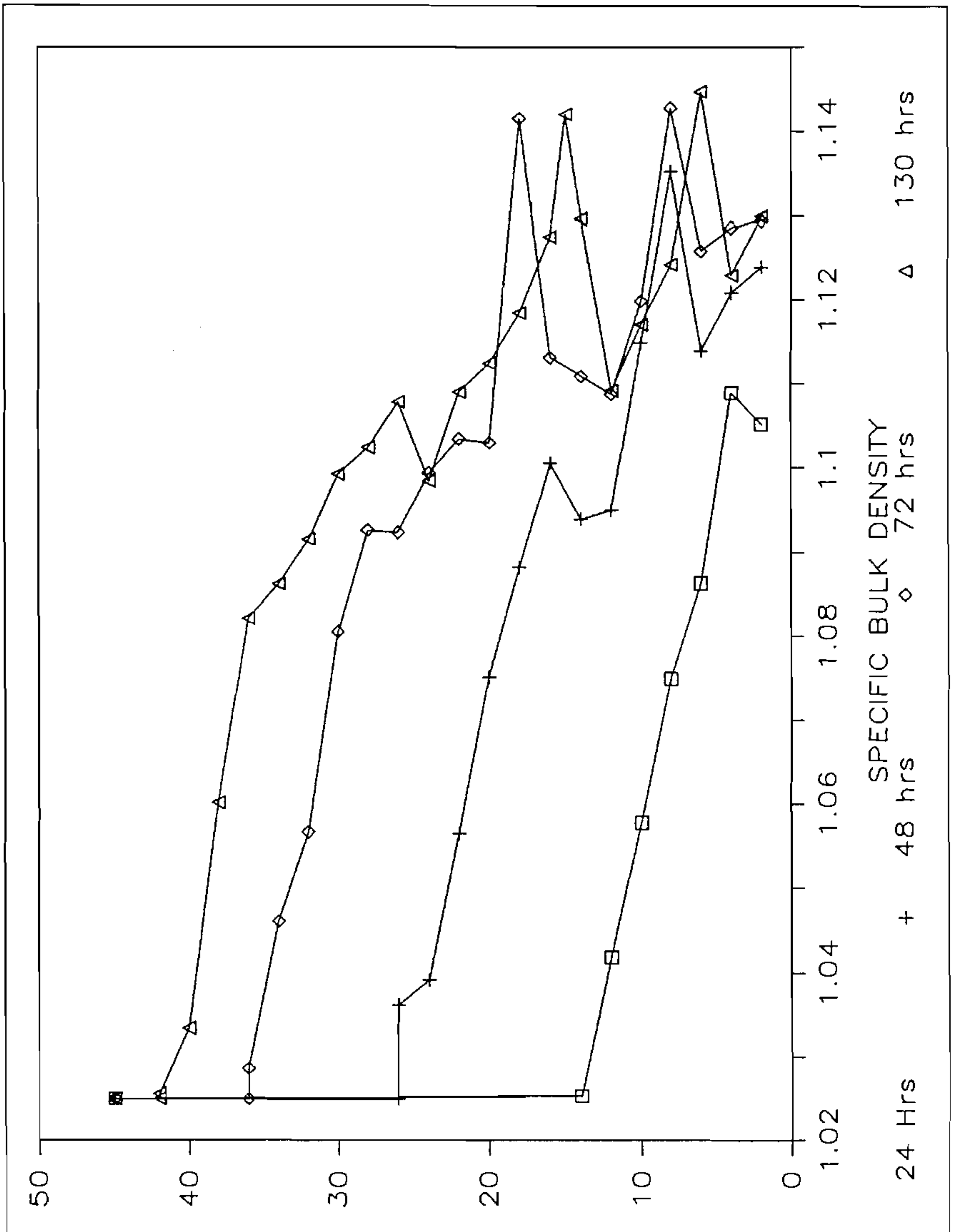



Fig A14 Test 6. Experimental bulk density profiles at 24 hour intervals

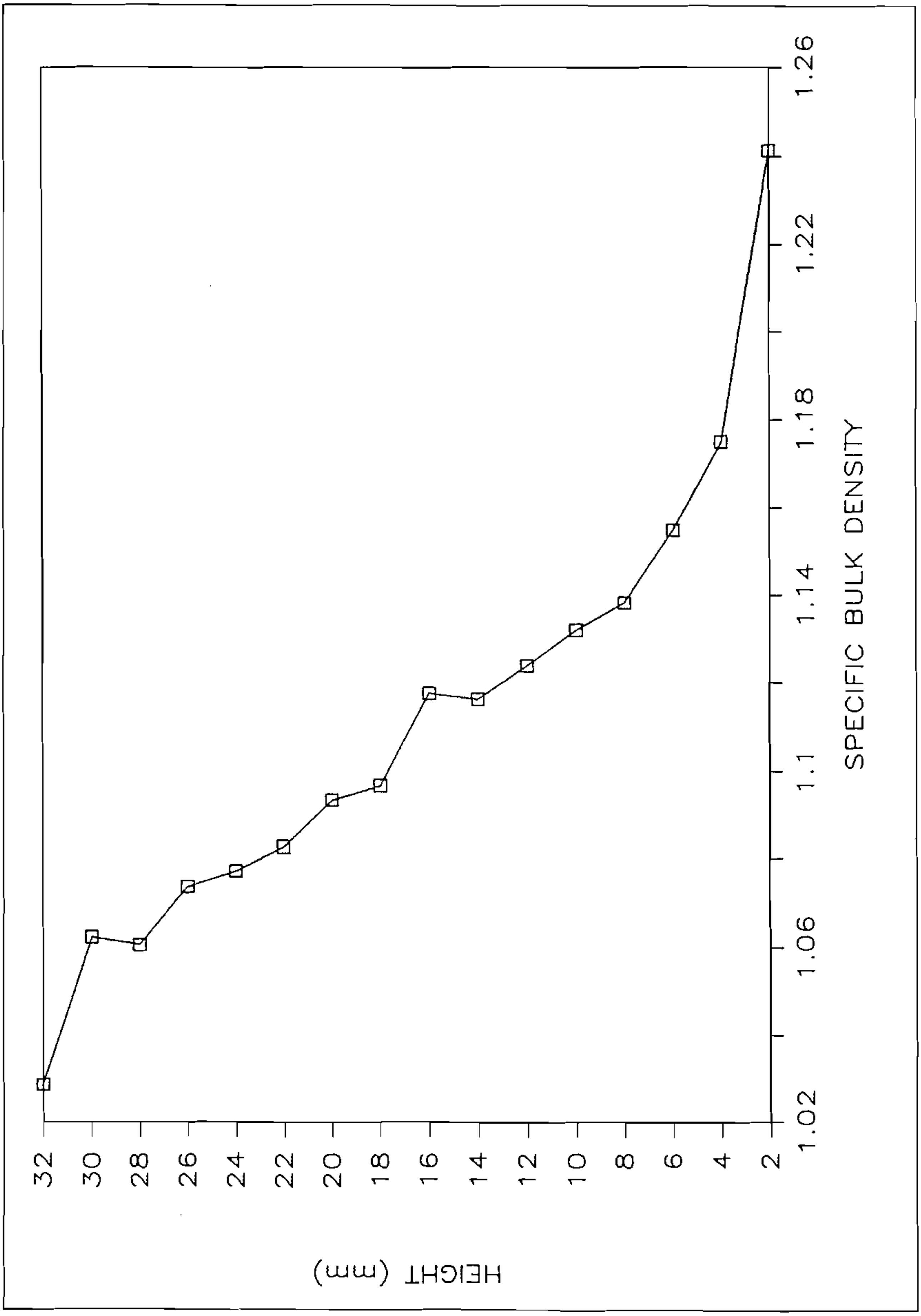



Fig A15 Test 7. Experimental bulk density profile after 24 hours

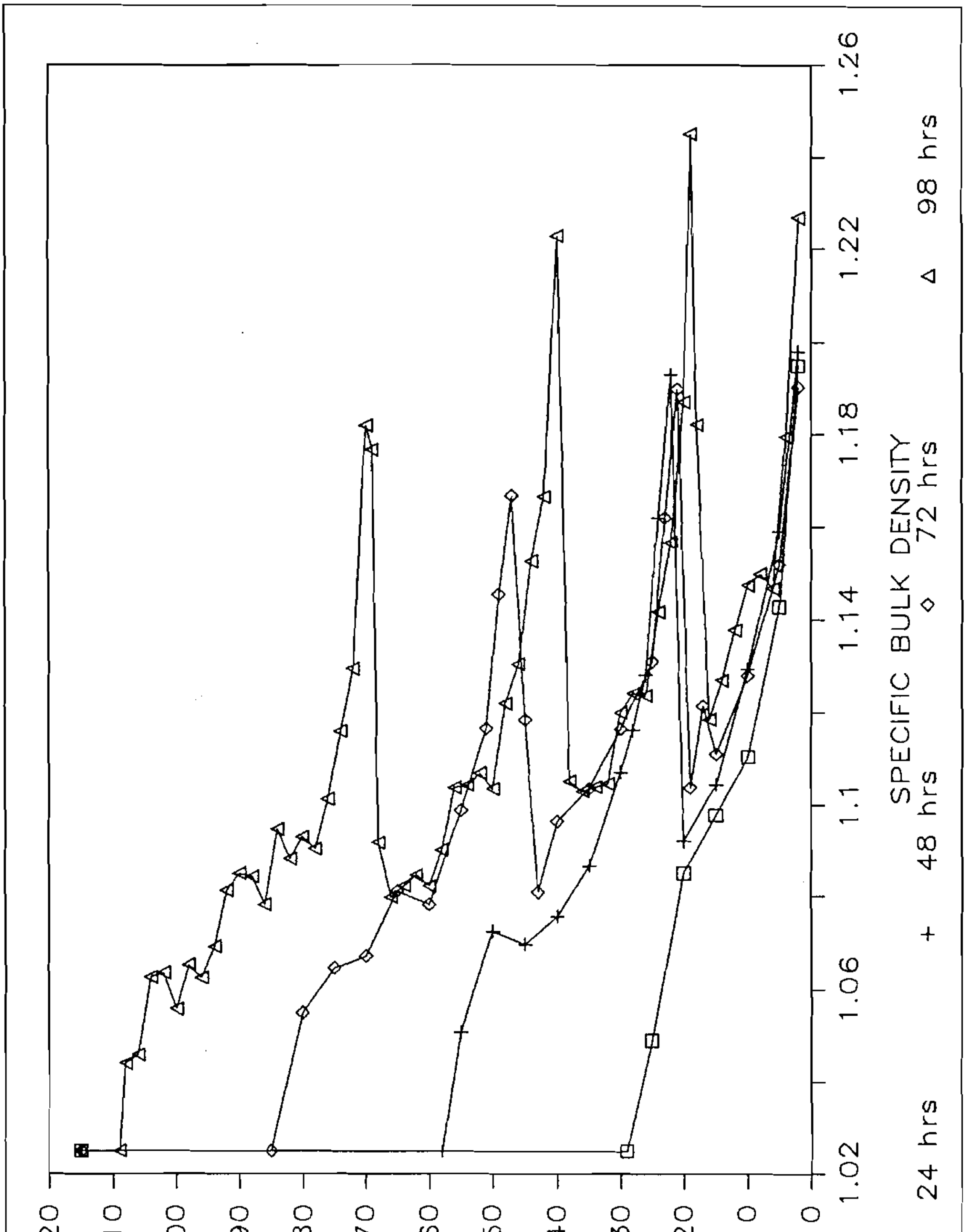



Fig A16 Test 8. Experimental bulk density profiles at 24 hour intervals