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DEPOSITION OF COHESIVE SEDIMENT FROM FLOWING WATER

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CONTRACT

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ABSTRACT

The ability to predict the movement of cohesive sediment within coastal, estuarine or inland waters is crucial to both the technical and financial viability of many existing and proposed engineering works. In particular, the capital and maintenance dredging requirement of a project may form a substantial part of the overall cost of that project. Good predictive measures to forecast the likely rates of settlement of cohesive sediment from suspension are essential to projects which have an element of dredging within them. The process of deposition of cohesive sediment is controlled by a complex combination of physical and chemical factors which are not fully understood. The size, strength and settling velocity of the settling units of a cohesive sediment are the results of flocculation. These units, or flocs comprise aggregates of flocs which stick together as a result of collisions. The lowest order floc comprises an aggregate of the primary particles but may have a settling velocity perhaps two or three orders of magnitude greater.

Parameters which influence flocculation include the size, mineralogy, ph and ionic strength of the particles, the solids concentration of the suspension, the chemical composition of the suspending water and hydrodynamic parameters such as shearing rates within the suspension and the bed shear stress. The study of the deposition of cohesive sediment within both the laboratory and the field environments is a difficult task. Although, the first investigations of cohesive sediments were carried out over twenty-five years ago (see Delo and Burt (1986) for a general review of research) it is reasonable to conclude that there remains considerable areas where the knowledge of sediment behaviour is lacking. The aim of the investigation described in this report was to define more precisely by experimental study the deposition of cohesive sediment from suspension with the objective of improving the predictive techniques of estimating the siltation in dredged channels.

A substantial number of tests were conducted in the carousel flume to examine the settling of cohesive sediment from flowing water. The initial series of tests were at steady flow in which the concept of proportional settling, the dispersed particle size grading of the suspension, the effect of salinity and the effect at the shear stress history were investigated. A second series of tests were undertaken in decelerating flow for the purpose of evaluating a theory of settling termed the distributed sediment model.

Proportional settling was observed in the steady flow tests in which the ratio of the equilibrium solids concentration at the reduced bed shear stress to the initial solids concentration at the high bed shear stress was found to be independent of the initial solids concentration. The value of the ratio decreased with decreasing bed shear stress until it reached zero at a bed shear stress of approximated $0.05 N/m^2$.

No consistent pattern in the change in dispersed particle size as a result of deposition could be identified. The effect of salinity on the settling of sediment from a flowing suspension was not consistent. The influence of shear stress history on the deposition of material from suspension was consistent.

Based on work by Mehta (1986) a distributed sediment model was presented. The principal assumptions of the model were: that the sediment could be divided into N classes each having a unique settling velocity, concentration and shear strength; that the distribution of settling velocities is

analagous to the initial distribution of concentration; and that the shear strength of the sediment in a class is related by a positive power law to the settling velocity. The model was calibrated by first selecting an appropriate settling velocity distribution based on results from a quiescent deposition test. The distributed sediment model was applied to predicting the deposition of suspended material during decelerating flow in the carousel. The predictions when compared with the laboratory data were sometimes greater, but, overall were generally somewhat lower.

Application of the distributed sediment model to the field situation and prediction of siltation at a particular point within a prescribed near bed suspended solids concentration and bed shear stress regime was presented. Comparison between the distributed and uniform sediment models for a range of typical concentration and bed shear stress regimes revealed that the distributed model gave siltation rates half an order of magnitude higher.

At this stage, the distributed sediment model is recommended to be used in a secondary capacity to the more usual uniform sediment model. Its value at present is in driving an upper bound estimate of siltation rates. Field measurement of in-situ changes in bed level and density coupled with comprehensive descriptions of the velocity and solids concentration profiles in the near bed region of a muddy estuarine site is strongly needed to prove the predictive capability of both the uniform and distributed sediment models.

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1 INTRODUCTION

The ability to predict the movement of cohesive sediment within coastal, estuarine or inland waters is crucial to both the technical and financial viability of many existing and proposed engineering works. In particular, the capital and maintenance dredging requirement of a project may form a substantial part of the overall cost of that project. Good predictive measures to forecast the likely rates of settlement of cohesive sediment from suspension are essential to projects which have an element of dredging within them.

The process of deposition of cohesive sediment is controlled by a complex combination of physical and chemical factors which are not fully understood. The size, strength and settling velocity of the settling units of a cohesive sediment are the results of flocculation. These units, or flocs comprise aggregates of flocs which stick together as a result of collisions. The lowest order floc comprises an aggregate of the primary particles but may have a settling velocity perhaps two or three orders of magnitude greater. Parameters which influence flocculation include the size, mineralogy, ph and ionic strength of the particles, the solids concentration of the suspension, the chemical composition of the suspending water and hydrodynamic parameters such as shearing rates within the suspension and the bed shear stress.

The study of the deposition of cohesive sediment within both the laboratory and the field environments is a difficult task. Although, the first investigations of cohesive sediments were carried out over twenty-five years ago (see Delo and Burt (1986) for a general review of research) it is reasonable to conclude that there remains considerable areas where the knowledge of sediment behaviour is lacking. This comment is more the result of the complexity of the study material rather than the performance of the numerous researchers who have in fact greatly contributed to attaining insights into the way in which cohesive sediments act.

The settlement or deposition of cohesive sediment from flowing water was first investigated by Krone (1962), Partheniades (1962) and Postma (1962). Since then, principally Mehta and Partheniades (1973), Dixit et al (1982) and Burt and Game (1985) have continued the research. The results of these studies do not need to be reviewed in detail although some findings are discussed where necessary later in the report. It is sufficient to highlight at this stage their outcome in terms of the algorithms which have evolved for predicting the deposition of cohesive sediment.

It is a well documented and accepted fact that at a certain low value of bed shear stress (denoted as τ_d) all suspended cohesive sediment will deposit from a flowing suspension. The rate at which the sediment deposits at flows below this critical shear stress is commonly expressed by:

$$\frac{dc}{dt} = -p\, W_s c \qquad (1)$$

in which c is the suspended solids concentration, p is the probability of a floc sticking to the bed and W_s is the floc settling velocity. The probability function is usually linear and takes the value 1 when the flow is stationary and 0 when the bed shear stress is equal to τ_d. The floc settling velocity can be determined by in-situ field measurement using the Owen tube, as reported by Owen (1971). A median value can be used as a representative settling velocity for use in Equation (1).

It has been recognised, however, from laboratory experiments that some cohesive sediment does deposit at bed shear stresses greater than τ_d. Although this deposit is only a proportion of the total sediment originally in suspension, it has been found that the proportion is somewhat independent of the solids concentration. The fraction which can deposit is inversely proportional to the bed shear stress, being 100% at a bed shear stress of τ_d, and 0% at a high bed shear stress defined as τ_m. Complicated relationships for determining the product pW_s in Equation (1), known as the apparent settling velocity, have been derived by Hayter and Mehta (1982) for their circular flume.

The concept of proportional settling described above raises important issues with respect to the application of the probability function outlined earlier which in effect prevents deposition at a bed shear stress equal to or above the value of τ_d. Proportional settling indicates that a considerable amount of deposition can occur at bed shear stresses considerably greater than the supposed limit of τ_d. These differences have to some degree been recently addressed by Mehta (1986) in the presentation of a model to represent the settling of a distributed sediment as opposed to a uniform sediment. This model is described in detail later in the report and tested against experimental data obtained in this present study.

It is reasonably clear from the preceding discussion that there was a need for further research into the deposition of cohesive sediment from flowing water. Hydraulics Research have recently commissioned (Burt and Game, 1985) a large annular flume for the study of cohesive sediment transport. The aim of the investigation described in this report was to define more precisely by experimental study the deposition of cohesive sediment from suspension with the objective of improving the predictive techniques of estimating the siltation in dredged channels.

2 THE CAROUSEL

2.1 Description

The carousel (Fig 1) consists of an annular flume, with an outer diameter of 6m, a channel width 0.4m and depth of 0.35m, and has a detachable roof 0.09m thick. The flume stands approximately 1.1m off the ground, supported by 12 brick pillars. The channel and the roof are constructed of fibre glass, with a 0.12m long perspex section in the channel for viewing. The roof fits into the channel, and floats on the fluid. Fluid motion in the carousel is induced and continued by the drag between the roof and the fluid surface as the roof rotates.

The driving mechanism for the roof consists of a DC Torque motor with a drive wheel, which turns a horizontal plate around the central spindle. It is to this plate that the drive arm is attached at one end (via the strain gauge) and to the roof at the other.

The strain gauge is used to measure the force applied to the roof of the carousel as it rotates. It consists of a spring and displacement transducer arrangement attached to the driving arm at the point of contact with the roof. The magnitude of the applied force is determined by the displacement transducer deflection, which is displayed on a chart recorder. The strain gauge is calibrated by applying known forces via a pulley system.

The speed of the motor, and hence roof speed, is controlled by a microcomputer. The motor speed can be set to an accuracy of 0.1% of the maximum speed. This produces a mean water velocity range in the flume from zero to approximately $0.7ms^{-1}$, with a corresponding applied shear stress range from zero to approximately $0.7N/m^2$.

The sampling system in the carousel consists of two port holes, one on each wall of the flume, 80mm above the floor. Through each of these port holes protrudes an 'L' shaped stainless steel sampling tube, which has an internal diameter of 2mm. The outer wall sampling tube has its entrance facing upstream and its elevation can be altered by rotating the outer portion of this tube across a scale corresponding to 0-100mm above the flume floor.

Fluid is continuously extracted from the carousel by a peristaltic pump and passed through a constant temperature water bath and a densiometer before being returned to the carousel. The densiometer works on the principle of determining the frequency of a thin vibrating glass tube through which the fluid is pumped and comparing this to the frequency of clean water pumped through a second densiometer. The readings obtained are analysed and displayed on a chart recorder. Bottle samples of the fluid are taken from time to time and analysed gravimetrically to maintain an accurate calibration. In this manner it is possible to measure the suspended sediment concentration of the fluid in the carousel continuously to within a few percent. It has been shown in previous measurements by Burt and Game (1985) that the mean suspended solids concentration of the fluid in the carousel is very close to the suspended solids concentration at the centre of flow, certainly less than 5% difference.

The thickness of the bed in the carousel is measured from beneath the flume at the perspex viewing section by an ultrasonic transducer. This instrument displays a peak in a signal which indicates the interface between the mud bed and the overlying fluid and enables the thickness of the bed to be determined to within 0.1mm. The transducer is calibrated through a fluid with a salinity similar to that in the mud bed. A moveable mounting device holds the tranducer in contact with the underside of the perspex section and is used to position the transducer at any point across the 0.4m width of the flume. In this way it is possible to obtain profiles of the bed and determine the depth of erosion at any time during the test.

2.2 Bed shear stress measurement

Two methods were employed for measuring the average shear stress exerted by the fluid on the bed. The first method was simple and involved direct measurement of the energy input to the roof through the calibrated strain gauge for a number of different speeds of rotation of the roof.

The second and more complex way of determining the bed shear stresses was by measurement of the near bed velocity profiles in the flume using laser doppler anemometry. The friction velocity at the bed was determined from a log-linear plot of height above bed and tangential velocity. Velocities were determined at three sections across the width of the flume for different speeds of rotation of the roof. The bed shear stresses were then computed from the logarithmic portion of the velocity-depth profiles.

The bed shear stress at the three sections across the width of the flume measured by the laser velocity meter is shown in Figure 2. Also given in Figure 2 is the average shear stress on the wetted perimeter given by the power input measured through the strain gauge and the width averaged shear stress from the laser measurements. These two curves show reasonable agreement and indicate a steady increase in bed shear stress with increasing speed of rotation of the roof. For the purpose of estimating the bed shear stress during a deposition test the curve representing the bed shear stress 0.06m from the inside wall of the carousel was used. It must be appreciated however, that the fluid in a test may have a high concentration of suspended solids and will not exhibit exactly the same hydrodynamic behaviour as the clean water used in the calibration. Nevertheless, it is considered that for the concentrations of suspended solids present in the carousel during a deposition test ($<5kg/m^3$) this factor would not significantly effect the estimation of the bed shear stress.

2.3 Suspension preparation

The filling and emptying processes involved with the carousel are shown schematically in Figure 3. Before a suspension is put into the carousel, it is first mixed homogeneously. This is achieved by putting the mud and water into the mixing tank and pumping the fluid through the recirculatory system.

The suspension is then pumped into the flume from the tank until the required depth of suspension in the flume is reached. The roof is lowered onto the surface of the fluid and the test is ready to start. After the test has been completed the roof is raised and either the suspension is re-mixed by hand or removed from the carousel through the drain and a new suspension prepared.

3 INITIAL LABORATORY TESTS

3.1 Concept of proportional settling

A number of tests were undertaken in the carousel to ensure that the results were consistent with those of Burt and Game (1985) and Mehta (1973) who had both observed proportional settling. One typical series of results obtained are shown in Figure 4. The depth of suspension was 0.1m, the initial solids concentration was close to $1.1kg/m^3$, the salinity was $32kg/m^3$ and the suspension was first stirred by hand and then rotated in the carousel flume for 1 hr at a bed shear stress of approximately $0.57N/m^2$, following which the speed of rotation was reduced quickly to values of 0.23, 0.12, 0.07, 0.05 and $0.00N/m^2$ respectively. The plots of the concentration of suspended sediment at the centre of the flow with time (Fig 4) indicate the effect of the prevailing bed shear stress.

At the highest bed shear stress the concentration falls only slightly and attains an equilibrium concentration just above $0.8kg/m^3$. This equilibrium value is further reduced as the bed shear stress is reduced to $0.12N/m^2$ and to $0.07N/m^2$. However, a further small reduction in the bed shear stress to $0.05N/m^2$ resulted in the continuous deposition of material and no equilibrium concentration being reached. In fact, all the material would eventually be deposited from the flowing suspension.

The ratio of the equilibrium concentration c_e, to the initial concentration c_o was found to be reasonably constant which was in agreement with other researchers' findings (see Mehta, 1973 Burt and Game, 1985). This is illustrated by the plots in Figures 5 to 8 which depict the variation in the dimensionless proportional concentration parameter $c(t)/c_o$ with time for sudden reductions in bed shear stresses to 0.36, 0.23, 0.12 and $0.07N/m^2$ respectively from an initial value of $0.57N/m^2$. The initial concentrations of the tests which are shown in each figure ranged between $0.5-5.0kg/m^3$. Although, the points given in each figure tend to vary from test to test the general impression is that the final equilibrium ratio is sensibly independent of the initial concentration.

The equilibrium proportional concentrations of all the tests conducted in which the bed shear stress was suddenly reduced from an initial high value are plotted with bed shear stress in Figure 9. A tentative line has been sketched through the points to illustrate the likely overall relationship. Below a certain critical shear stress τ_d, all the sediment in suspension eventually deposits. This critical value appears to be approximately $0.05N/m^2$ which is consistent with the curves depicted in Figure 4 showing that at a shear stress of $0.05N/m^2$ all the sediment appears to deposit.

3.2 Size distributions of primary particles

Although it was not possible to measure the in-situ size distribution of the flocs during deposition it was possible to withdraw a small quantity of the suspension from the carousel and measure the dispersed particle size distribution. Samples were taken from a number of tests and the results of the particle size analysis used to assess the likely composition of primary particles in the flocs at equilibrium concentrations.

The pairs of curves shown in Figures 10 to 13 are the dispersed particle size distributions at the initial suspended sediment concentration (ie at a bed shear stress of $0.57N/m^2$) and the equilibrium suspended sediment concentration at the reduced bed shear stress. These examples were selected as being illustrative of the overall results of the size distributions.

The general impression obtained from the curves shown, and indeed from all the results, is that there does not appear to be a consistent pattern in the dispersed particle size distributions. In some tests the size distribution remained reasonably constant throughout deposition (eg Figs 10 and 12) and in other tests the primary particles were somewhat finer at the lower bed shear stress after deposition (eg Figs 11 and 13). In only a few tests did the equilibrium sediment suspension have a coarser size distribution (Fig 12 illustrates this to some degree).

The variation from test to test may be accounted for by a number of factors including differences in the initial size distribution of sediment, unrepresentative sampling due to only small volumes being withdrawn and the effect of complex flocculation processes. It is possible to conclude from the size distributions, however, that deposition of the sediment must in many cases be taking place by flocculation which is forming flocs comprising the entire range of primary particle sizes. Whether or not any individual floc contains a range of sizes of primary particles or is composed principally of just one size which varies from floc to floc cannot be deduced from the data.

The size distributions of the primary particles for the tests with no salinity show a clear trend for sorting the sediment with respect to particle diameter for the given bed shear stress. An example of some typical size distributions for no salinity are shown in Figure 14. In this case, due to the reduced flocculation between the primary particles, the bed shear stress tends to control the size distribution of the suspension in much the same way as with incipient motion of cohesionless sediment. As the bed shear stress is reduced the minimum diameter of particle which falls out of suspension is decreased thus allowing finer particles to be deposited at the lower bed shear stresses.

3.3 Effect of salinity

The influence of three different salinities ($32kg/m^3$, $5kg/m^3$ and zero) was assessed by running tests with approximately the same initial solids concentration of suspension ($\sim 1.0kg/m^3$) and reducing the bed shear stress, after 1 hour at $0.57N/m^2$, to $0.36N/m^2$, $0.07N/m^2$ and $0.0N/m^2$ respectively. The results of selected typical tests are shown in Figures 15, 16 and 17. The results in the figures do not give a consistent pattern for the influence of salinity on the deposition of suspended sediment. It appears that the effect of salinity depends on the bed shear stress during deposition, although, it must be pointed out that the results presented here are not exhaustive. At a bed shear stress of $0.36N/m^2$ (Fig 15) a suspension with no salinity deposits slightly more and a much quicker rate than a suspension with a salinity of $5kg/m^3$. For a lower bed shear stress of $0.07N/m^2$ (Fig 16) a suspension with no salinity initially deposits faster but has a higher equilibrium concentration than a corresponding suspension with 32kg/m^3 salinity. When the deposition of suspended sediment occurs in quiescent conditions (Fig 17), the effect of salinity is more marked with the rate of deposition increasing with salinity.

3.4 Effect of shear stress history

It has been clearly shown that the bed shear stress plays an important role in determining the equilibrium concentration of suspended sediment. The tests which indicated this response followed a similar pattern in that the sediment was initially suspended for 1 hour at a high bed shear stress after which the bed shear stress was reduced abruptly. Two series of tests were conducted, however, to investigate the effect of the bed shear stress history on the equilibrium concentration of suspended sediment. These tests took the form of a two stage reduction in bed shear stress. Each stage lasted 21 hours and the equilibrium concentrations are presented in Table 1 with the bed shear stress.

The trend in the results is clear although small in magnitude. The effect of the intermediate bed shear stress value is to increase the final equilibrium concentration of suspended sediment by an amount which has a maximum value at a bed shear stress somewhere between the initial high value and the final reduced value. For the first series of tests given in Table 1 (ie D7/1 to D7/4) the final bed shear stress was 0.07N/m^2 and the intermediate values were 0.36, 0.23 and 0.12N/m^2 respectively, with test D7/4 in effect having an intermediate shear stress of 0.07N/m^2. Because the tests began and ended at equilibrium suspended solids concentrations, intermediate bed shear stresses very close to 0.57

and 0.07N/m^2 would not by definition have any effect on the final equilibrium concentration. In terms of proportional concentrations the intermediate bed shear stress of 0.23N/m^2 gave the maximum increase with a final value of 0.44 compared with 0.40 for the direct reduction to 0.07N/m^2. Intermediate stresses either side of 0.23N/m^2 gave corresponding smaller increases in the final equilibrium concentration - 0.36N/m^2 resulted in a proportion of 0.41 and 0.12N/m^2 gave 0.42.

A similar pattern was recorded in the second series of tests D7/5 to D7/7 for which the final bed shear stress was 0.12N/m^2. A straight reduction to 0.12N/m^2 produced an equilibrium proportional concentration of 0.53, whereas, an intermediate stress of 0.23N/m^2 raised this value to 0.59 and a stress of 0.36N/m^2 increased it to 0.56.

At this present time interpretation of these findings is a little difficult other than to postulate that the floc size distribution or shear strength of flocs must be effected by the intermediate shear regime. This results in less sediment being deposited compared to having no intermediate bed shear stress. It may be concluded that the flocs have become weaker and less able to withstand the high shear rates near the bed and/or smaller in size with lower effective settling velocities.

4 DISTRIBUTED SEDIMENT MODEL

4.1 Description

The original concept of a critical shear stress τ_d, and settling velocity W_s, to describe the behaviour of deposition from a suspended sediment with a concentration between 0.1 to $1 kg/m^3$ proposed by Krone (1962) and given as Equation (1) is adequate for highly cohesive clayey sediments which form strong aggregates of uniform composition. When the sediment is coarser, with silt particles as well as clay particles, and is less cohesive, the depositional behaviour is different from a uniform sediment in that both τ_d and W_s have distributions that are probably related in some way to either size or concentration. A distributed sediment model based on this assumption was presented by Mehta (1986) and has been adopted in this study with the objectives of determining its ability to predict deposition from continuous decellerating flow in the carousel flume and assessing its likely benefit in predicting siltation of cohesive sediment in the field.

The model has three principal assumptions. First, the sediment is considered to be divided into N classes each having a unique settling velocity, concentration and critical shear stress for deposition. Hence, the solution for Equation (1) can be redefined as:

$$C_t = \sum_{i=1}^{N} C_i = \sum_{i=1}^{N} C_{0i} \exp\left[-\left(1 - \frac{\tau_b}{\tau_{di}}\right) \frac{W_{si}}{h}\right] t \qquad (2)$$

where for all τ_b τ_{di} in a given class i, $C_i = C_{oi}$.

The second assumption is that the relationship between the settling velocity and suspended sediment concentration can be given by:

$$W_s = kc^n \qquad (3)$$

with n = 1. This is the simplest case which is within the range of values found for well aggregated sediments in settling columns (ie 0.8 to 2.0). This selection implies that the distribution of settling velocity, $\phi(W_{si})$, of the distributed sediment would be analagous to the associated distribution, $\phi(C_{0i})$, of initial concentrations, C_{0i}, hence

$$C_{0i} = \phi(C_{0i}).C_0 = \phi(W_{si}).C_0 \qquad (4)$$

The third assumption is that a power law relationship exists between the critical shear stress, τ_{di}, and the corresponding W_{si}, specified as:

$$\tau_{di} = k_\tau W_{si}^{m} \qquad (5)$$

where k_τ would be numerically equal to τ_d, the critical shear stress for uniform sediment, for which M = 0. Mehta defines the lowest value of τ_{di} as τ_{dl} which is the critical shear stress below which all sediment eventually deposits. The associated minimum settling velocity is W_{sl}. Likewise, the corresponding maximum values are τ_{dN} and W_{sN}. Combining Equations 2, 4 and 5 and substituting for k_τ and m leads to

$$\frac{C}{C_0} = \frac{1}{C_0}\sum_{i=1}^{N} C_i = \sum_{i-1}^{N} \phi(W_{si}) \exp\left\{-\left[1-\frac{\tau_b}{\tau_{dl}}\left(\frac{W_{sl}}{W_{si}}\right)^{\left[\frac{\ln(\tau_{dN}/\tau_{dl})}{\ln(W_{sN}/W_{sl})}\right]}\right]\frac{W_{si}}{h}\right\} t \qquad (6)$$

For a uniform sediment, this reduces to

$$C = C_0 \exp\left[-\left(1-\frac{\tau_b}{\tau_d}\right)\frac{W_s}{h}\right] t \qquad (7)$$

4.2 Calibration

To use the model it was necessary to determine the settling velocity distribution of the flocculated sediment at the beginning of the test at the bed shear stress of $0.57 N/m^2$, the maximum bed shear stress, τ_{dN}, above which no deposition at all could take place and the characteristic minimum critical bed shear stress, τ_{dl}, below which all sediment deposits. These parameters were determined by experiments in which the bed shear stress was suddenly reduced, as described in the preceding chapter. Having calibrated the model, it was applied in simulating the deposition of a distributed flocculated sediment from a continuously decellerating flow (see following section).

The settling velocity distribution, $\phi(W_{si})$, was derived from the results of a quiescent settling test in which a suspension of sediment with an initial concentration of 0.777kg/m^3 was mixed at a bed shear stress 0.57N/m^2 for 1 hour and then allowed to deposit at zero flow. The dispersed size grading of the suspended sediment was used in conjunction with Stokes settling velocity equation and a factor related to the particle size to give an estimated flocculated sediment settling velocity distribution. The velocity W_s, of a flocculated sediment of median dispersed particle size, D_{50} was found by Migniot (1968) to be approximately given by,

$$W_s = 0.9 \ D_{50}^{\ 2} \ F \tag{8}$$

where F, the flocculation factor was a function of particle size, ie,

$$F = 20^f \ D_{50}^{\ -f} \tag{9}$$

with F = 1.8 for $D_{50} < 0.020$m and f = 0 (ie F = 1) for $D_{50} > 0.020$m. This implied that the flocculation effect for a sediment with a median particle size of greater than 20μm was negligible.

In the present study the value of the flocculation factor, F was calculated for each class of distributed sediment for a particular value of the constant f. A second mathematical model was used to simulate the quiescent settling of a distributed flocculated sediment in suspension, assuming no change in the flocculation regime. The results from this model at mid-depth (ie the position of sampling tube in the carousel) were compared with the experimental data and the value of f was adjusted until a good fit was obtained, as illustrated in Figure 18. The settling velocity distribution with f = 0.7 resulted in a minimum settling velocity, W_{s1}, of 3.0E-06m/s and a maximum, W_{sN}, of 1.5E-04m/s.

The maximum bed shear stress, τ_{dN}, was taken to be equal to $1.0N/m^2$, similar to the value adopted by Mehta (1986). The model was not very sensitive to changes in this parameter.

The characteristic bed shear stress, τ_{d1}, was determined by running the distributed sediment model to simulate the tests shown earlier in Figures 5 to 8 in which the bed shear stress was reduced suddenly to 0.36, 0.23, 0.12 and $0.07N/m^2$ respectively. The value of τ_{d1} was varied until a good fit was obtained between the average of the test data for each magnitude of bed shear stress and the output from the model. These results are shown in Figures 19 to 22 respectively. Reasonably good fits were obtained in each case but the value of τ_{d1} was found to vary with the applied bed shear stress. This relationship is depicted in Figure 23 in which it may be seen that τ_{d1} generally increases as the magnitude of the applied bed shear stress is reduced.

For example, at a bed shear stress of $0.36N/m^2$, τ_{d1} was $0.010N/m^2$, whereas, at a bed shear stress of $0.07N/m^2$ the characteristic stress τ_{d1} was greater at $0.040N/m^2$. An approximate relationship was obtained by fitting the Equation (in N/m^2).

$$\tau_{d1} = 0.008\ (\tau_b + 0.6)^{-4} \qquad (10)$$

This relationship was used in the simulation of the continuously decellerating flow tests to calculate the appropriate time-varying value of τ_{d1} from the prescribed value of τ_b.

4.3 Prediction

The performance of the distributed sediment model was assessed by comparing the output from the model with the results of twelve decellerating flow tests in the carousel. These tests had linear rates of decreasing bed shear stress from an initial value of $0.57N/m^2$ which was maintained from a period of 1 hour at the beginning of each test. Three final bed shear stresses were adopted, ie 0.23, 0.07 and $0.00N/m^2$ together with times of reduction, ie 60, 180, and 360 minutes. In addition, a time of reduction of 120 minutes was run for the final bed shear stress of $0.00N/m^2$ and 120 and 240 minutes for the bed shear stress of $0.07N/m^2$. The values of $\phi(W_{si})$, τ_{dN} and τ_{d1} used in the model were as discussed in the preceeding section and were the same in each simulation run.

Plots of the experimental and model data are presented for Tests C1 to C12 in Figures 24 to 35 respectively. Prediction of the average suspended solids concentration for the decellerating flow tests with a final bed shear stress of $0.23N/m^2$ are consistently low compared to the experimental data (see Fig 24 (60 mins), Fig 25 (180 mins), and Fig 26 (360 mins). The discrepancy between model and experimental reduces as the time period for the linear reduction in bed shear stress increases. For instance, in Test C1 (Fig 24) the predicted average concentration of suspended solids after 60 minutes is $1.71kg/m^3$ compared with the concentration in the carousel experiment of $1.51kg/m^3$. In Test C3 (Fig 26), however, the predicted and experimental solids concentrations after 360 minutes are 1.37kg/m^3 and 1.45kg/m^3 respectively.

The five tests, C4 to C8, in which the bed shear stress was reduced to 0.07N/m^2 over time periods of 60, 120, 180, 240 and 360 minutes respectively are shown in Figures 27 to 31. The model generally under-estimated the concentration of suspended solids for time periods of 60 and 180 minutes and over-estimated the concentration for the majority of the test for time periods of 120 and 240 minutes. Reasonably good agreement between the model and the experimental data was found for the longest time period (360 minutes) as illustrated in Figure 31. In predicting the quantity of material deposited during these tests, the model over-estimates at worst by a factor of two.

Four tests were conducted in which the bed shear stress was reduced to zero over time periods of 60, 120, 180 and 360 minutes. The results of these tests (C9 to C12) are shown in Figures 32 to 35 respectively. Except for the shortest time period the model consistently under-estimates the concentration of suspended solids. In terms of material deposited, the model again predicts, on average, approximately twice as much as was deposited in the carousel flume test. For the 60 minute tests (Fig 32), the predicted concentration at the end was 1.21kg/m^3 compared with the experimental value of 0.96kg/m^3.

In summary, the distributed sediment model, when applied to decelerating flow and compared with results from laboratory tests gave predicted suspended solids concentrations which were generally lower than those measured experimentally. Some discussion of the assumptions made in the model and the implications for its application in the prediction of siltation from flowing water in estuarine environments are presented in the following chapter.

5 DISCUSSION

51. Assumptions

The distributed sediment is founded on a number of assumptions. Mehta (1986) made three principal assumptions in his derivation of the model (see Section 4.1), ie 1) the sediment can be considered as N discrete classes, 2) the settling velocity is directly proportional to concentration, and 3) a power law relationship holds between the shear strength of a sediment class and its settling velocity. These assumptions are embodied in Equations (2), (3) and (5) respectively. Of these, it is the third assumption which is the most difficult to justify. In fact, there is experimental evidence which contradicts this assumption. Krone (1963) in his rheological study of the properties of estuarial sediments found that the shear strength of aggregates decreased as their order increased, whereas, their settling velocity increased. Furthermore, Krone's view on the role of internal sheering both promoting and limiting the floc size implied a dynamic process of formation and break up of flocs, and hence, tends to weaken the argument for dividing the sediment into discrete classes.

In the calibration of the model, additional assumptions were made in order to derive a settling velocity distribution for the flocculated sediment at the beginning of a test and to identify a probable value of τ_{dN}. The factoring of the Stoke's settling velocity equation following work by Migniot (1968) (see Equation (9)) is somewhat tenuous as the study by Migniot was with reasonably homogenous sediments, whereas, the application was in a distributed sediment model. The value for τ_{dN} was known not to greatly influence the results of the model for values between 0.6 and $1.0N/m^2$.

However, the adoption of such a high value for τ_{dN} in comparison with the typical values of τ_d of $0.06-0.10N/m^2$ which have been widely used to define the shear stress at which deposition first takes place, clearly illustrates that deposition is assumed to take place at very much greater shear stress that has been previously envisaged. This opens up the question of simultaneous deposition and erosion. At present, the approach taken in this respect in modelling is to allow deposition of cohesive sediment to occur only during decelerating flows and conversely to allow erosion of material only during accelerating flows (Hayter and Mehta, 1986).

The period of quiescent settling immediately following a decelerating flow test was recorded in Tests C4 and C5 and compared with the prediction from the model developed for the determination of the flocculated sediment settling velocity. The results are shown in Figures 36 and 37 respectively. It is clear that the sediment in suspension in the carousel flume deposits more quickly than the predicted value from the model. This implies that the floc sizes in the laboratory flume were considerably larger and hence the settling velocities were higher, compared to those predicted by the model. This could have been the result either of rapid aggregation during the first few minutes of settling in quiescent conditions or, more likely, these larger flocs simply existed in the suspension at the end of the decelerating flow period.

5.2 Field application

5.2.1 Input parameters

The distributed sediment model requires as its fundamental input a histogram of the settling velocity distribution $\phi(W_{si})$. This distribution is often readily available from field settling velocity tests which in the past have been used principally to determine the median settling velocity, W_{50}. However, in the standard Owen tube procedure a complete settling velocity distribution is obtained from which W_{50} is estimated. This may easily be manipulated to give, for a particular suspended solids concentration, a distribution across N classes with the values of W_{s1} and W_{sN} appropriately identified.

The value of τ_{dN} has been found to be reasonably unimportant and it would be suggested that a value of $0.8 N/m^2$ be adopted. On the other hand, the results from the distributed sediment model are sensitive to changes in τ_{d1}. The tests in the carousel tended to indicate that τ_{d1} was a function to some degree of the applied bed shear stress and could take a value of between 0.01 and $0.04 N/m^2$ inversely dependent on the applied bed shear stress. In the absence of any further information, it is suggested that the relationship given in Equation (10) be used and that sensitivity analysis on τ_{d1} are conducted.

In the context of predicting the siltation at a particular point in a study area in the field the usual method would be to first derive the time-varying concentration of suspended solids near to the bed from either field monitoring or perhaps a depth-averaged numerical model. Over a short interval of time the mass to the bed, dM, would be calculated from

$$dM = W_{50}\, C_t\, (1 - \tau_b/\tau_{dc})\, \Delta t \qquad (11)$$

The median settling velocity, W_{50}, could be measured in the field and related to the solids concentration, C. The bed shear stress, τ_b, could also be derived from field measurement or determined from a physical scale model or numerical model. For all time intervals in which τ_b was less than τ_{dc} (typically 0.05 to 0.10N/m^2) the mass would be given by Equation (11) and summed to give a total over, say, one tidal cycle.

In the distributed sediment model the requirement for the time varying values of near bed suspended solids concentration and bed shear stress are the same as in the standard, uniform sediment model approach described above. However, for any near-bed concentration the distribution of settling velocities is also needed together with appropriate values of τ_{d1} and τ_{dN}. Over each time interval Δt, the prescribed sediment concentration is divided into N classes of W_{si} and τ_{di}. The total sediment deposited on the bed during a time interval is given by the summation of the individual amounts deposited from each class, ie:

$$dM = \sum_{1}^{N} W_{si}.\phi C_i.C_t.(1 - \tau_b/\tau_{di}).\Delta t \qquad (12)$$

A sediment class would deposit if $\tau_{di} > \tau_b$. As τ_{dN} is typically of the order of 0.6 to 1.0N/m^2 it is clear that some sediment will deposit at considerably higher bed shear stresses than given by Equation (11). One further limit in Equation (12) is that deposition is assumed to occur only during decelerating flows, whereas, for the uniform sediment no such restriction is applied other than $\tau_{dc} > \tau_b$.

5.2.2 Example

To assess the order of magnitude of predictions using the distributed sediment model in relation to those made with the normal uniform sediment model a number of comparative runs of each model were conducted for idealised time varying patterns of near bed suspended solids concentration and bed shear stress. A half tidal cycle period of 6 hours was adopted in which the near bed suspended solids concentration and bed shear stress both varied linearly from a maximum value at t = 0hrs to a minimum at t = 3hrs which remained constant until t = 3.5hrs and then increased linearly to the previous maximum value at t = 6hrs. The value of τ_{dc} used was $0.07N/m^2$. In the distributed sediment model, τ_{d1} was set to $0.02N/m^2$ and τ_{dN} to $0.8N/m^2$. The median settling velocity and settling velocity distributions as a function of solids concentration were taken from Thames field survey data (Burt and Stevenson, 1985).

For typical maximum and minimum values of the near bed suspended solids concentration and bed shear stress the mass per unit area deposited on the bed were calculated with the uniform and distributed sediment models. Maximum near bed concentrations were between 0.6 and $1.0kg/m^3$, with minimum values of between 0.2 to $0.4kg/m^3$. Corresponding maximum range for the bed shear stress was 0.3 to $1.0N/m^2$ with the minimum bed shear stress always equal to $0.0N/m^2$.

The result of the models were conclusive in that, although the mass predicted to deposit on the bed varied greatly in both models depending on the near bed suspended solids concentration and bed shear stress regimes, the ratio of the deposited mass predicted by the distributed sediment model to that predicted by the uniform sediment model was at least four. In some cases, the ratio was much higher, but, on average it was approximately six. For low bed shear stresses, the ratio, as would be expected, had lower values. As the maximum shear stress approaches τ_{dc} the difference between the models will diminish, until at the limiting case of $\tau_b = 0.0 N/m^2$ when the ratio will be unity.

These large differences between the distributed and uniform sediment models are still only hypothetical as both models are derived from the interpretation of laboratory data together with, in the case of the distributed sediment, a number of major assumptions regarding the settling velocity, shear strength and distribution of aggregates. Both of these models are in need of verification in the field by carefully instrumented test sites. Until such a field exercise can be attempted, the value of the distributed sediment model is limited. Its probable main area of worth at present would be in providing a secondary and upper bound calculation of siltation by considering a slightly different mechanism. One significant question mark over the distributed sediment model remains the validity of assuming that large flocs with high settling velocities found in the upper layers of an estuarine flow have high shear strengths which enable them to withstand the proportionally higher shearing rates near to bed and settle ahead of smaller flocs.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

1. A substantial number of tests were conducted in the carousel flume to examine the settling of cohesive sediment from flowing water. The

initial series of tests were at steady flow in which the concept of proportional settling, the dispersed particle size grading of the suspension, the effect of salinity and the effect at the shear stress history were investigated. A second series of tests were undertaken in decelerating flow for the purpose of evaluating a theory of settling termed the distributed sediment model.

2. Proportional settling was observed in the steady flow tests in which the ratio of the equilibrium solids concentration at the reduced bed shear stress to the initial solids concentration at the high bed shear stress was found to be independent of the initial solids concentration (Figs 5 to 8). The value of the ratio decreased with decreasing bed shear stress until it reached zero at a bed shear stress of approximated $0.05 N/m^2$ (Fig 9).

3. Samples of suspension were withdrawn at equilibrium concentrations of suspended solids and analysed for dispersed particle size distribution. No consistent pattern in the change in dispersed particle size as a result of deposition could be identified. Although, variation in size distributions could be attributed in part to experimental difficulties it was argued that the flocs settling to the bed in total comprised all sizes of primary particles.

4. The effect of salinity on the settling of sediment from a flowing suspension was not consistent. At a bed shear stress of $0.36 N/m^2$ a suspension with no salinity deposits more quickly than a suspension of salinity $5 kg/m^3$ (Fig 15).

In quiescent conditions, a suspension with a salinity of $32kg/m^3$ settled out more quickly than a suspension of salinity $5kg/m^3$, which in turn settled faster than a suspension of zero salinity (Fig 17).

5. The influence of shear stress history on the deposition of material from suspension was consistent. For the pattern of successive steady flow shear stresses investigated it was found that the final equilibrium concentration could be changed by up to approximately 10% depending on the intermediate bed shear stresses (Table 1).

6. Based on work by Mehta (1986) a distributed sediment model was presented. The principal assumptions of model were: that the sediment could be divided into N classes each having a unique settling velocity, concentration and shear strength; that the distribution of settling velocities is analagous to the initial distribution of concentration; and that the shear strength of the sediment in a class is related by a positive power law to the settling velocity. The model was calibrated by first selecting an appropriate settling velocity distribution based on results from a quiescent deposition test. Values of τ_{d1} were obtained by fitting the model result to laboratory test data for a constant value of τ_{dN} of $1.0N/m^2$. The value of τ_{d1} was found to vary inversely with τ_b (Fig 23).

7. The distributed sediment model was applied to predicting the deposition of suspended material during decelerating flow in the carousel. The predictions when compared with the laboratory data were sometimes greater, but, overall were generally somewhat lower.

8. The assumption of the positive power law relationship between the shear strength of the sediment aggregates within a class and the settling velocity was identified as the most tenuous. Krone (1963) had in fact measured the opposing trend.

9. Application of the distributed sediment model to the field situation and prediction of siltation at a particular point within a prescribed near bed suspended solids concentration and bed shear stress regime was presented. Comparison between the distributed and uniform sediment models for a range of typical concentration and bed shear stress regimes revealed that the distributed model gave siltation rates half an order of magnitude higher.

6.2 Recommendations

1. At this stage, the distributed sediment model is recommended to be used in a secondary capacity to the more usual uniform sediment model. Its value at present is in deriving an upper bound estimate of siltation rates.

2. Field measurement of in-situ changes in bed level and density coupled with comprehensive descriptions of the velocity and solids concentration profiles in the near bed region of a muddy estuarine site is strongly needed to prove the predictive capability of both the uniform and distributed sediment models.

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TABLE.

TABLE 1 Equilibrium concentation and bed shear stress history for steady flow deposition tests: No salinity

TEST No	TIME Hours	BED SHEAR STRESS N/m^2	EQUILIBRIUM CONCENTRATION kg/m^3	PROPROTION CONCENTRATION cf/c0
D7/1	1	0.57	0.98	
	22	0.36	0.81	
	43	0.07	0.40	0.41
D7/2	1	0.57	1.01	
	22	0.23	0.64	
	43	0.07	0.44	0.44
D7/3	1	0.57	1.03	
	22	0.12	0.55	
	43	0.07	0.43	0.42
D7/4	1	0.57	0.98	
	22	0.07	0.38	0.40
D7/5	1	0.57	1.02	
	22	0.36	0.89	
	43	0.12	0.58	0.56
D7/6	1	0.57	1.05	
	22	0.23	0.70	
	43	0.12	0.62	0.59
D7/7	1	0.57	1.03	
	22	0.12	0.55	0.53

FIGURES.

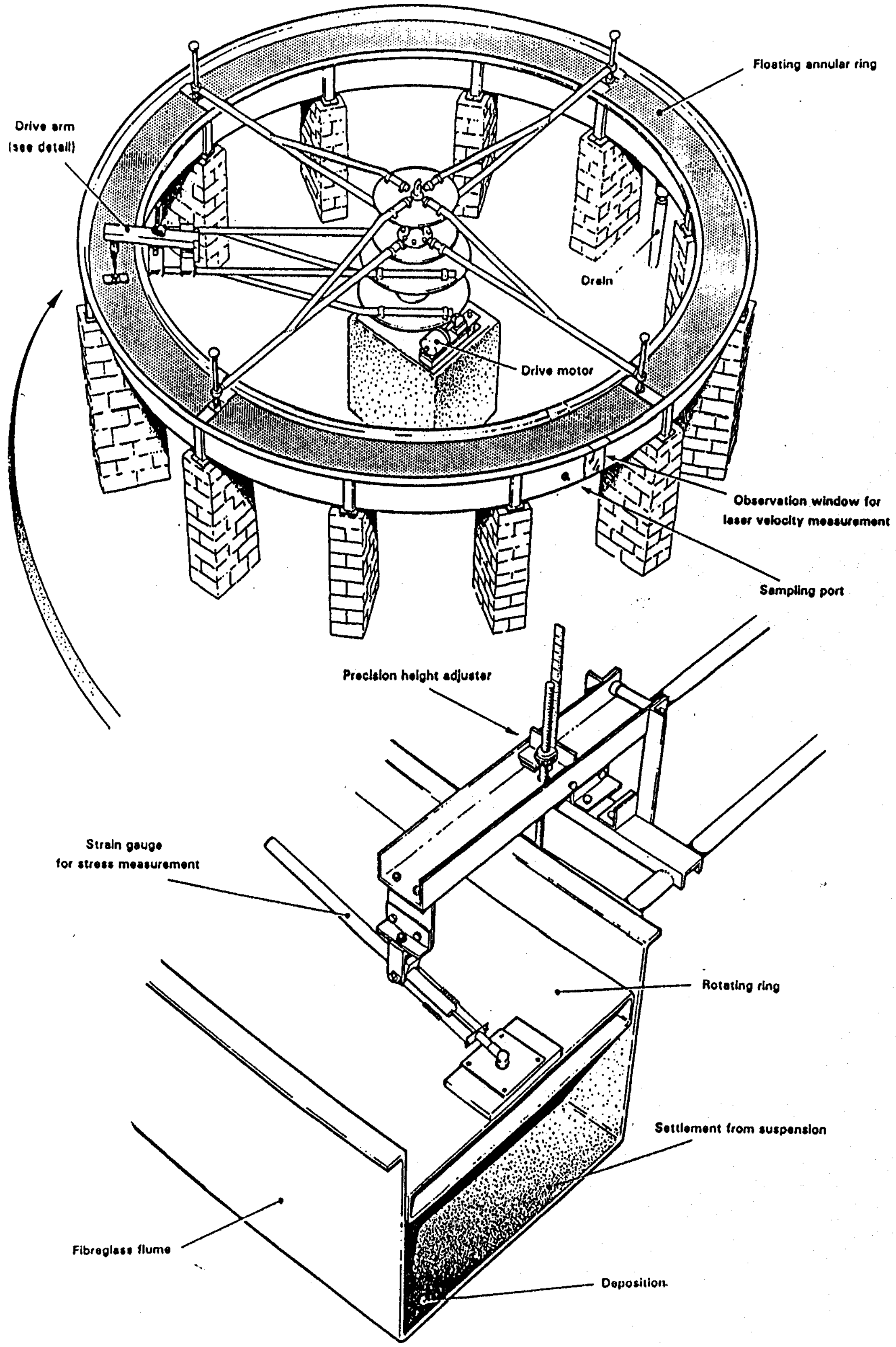

Fig 1 The Carousel

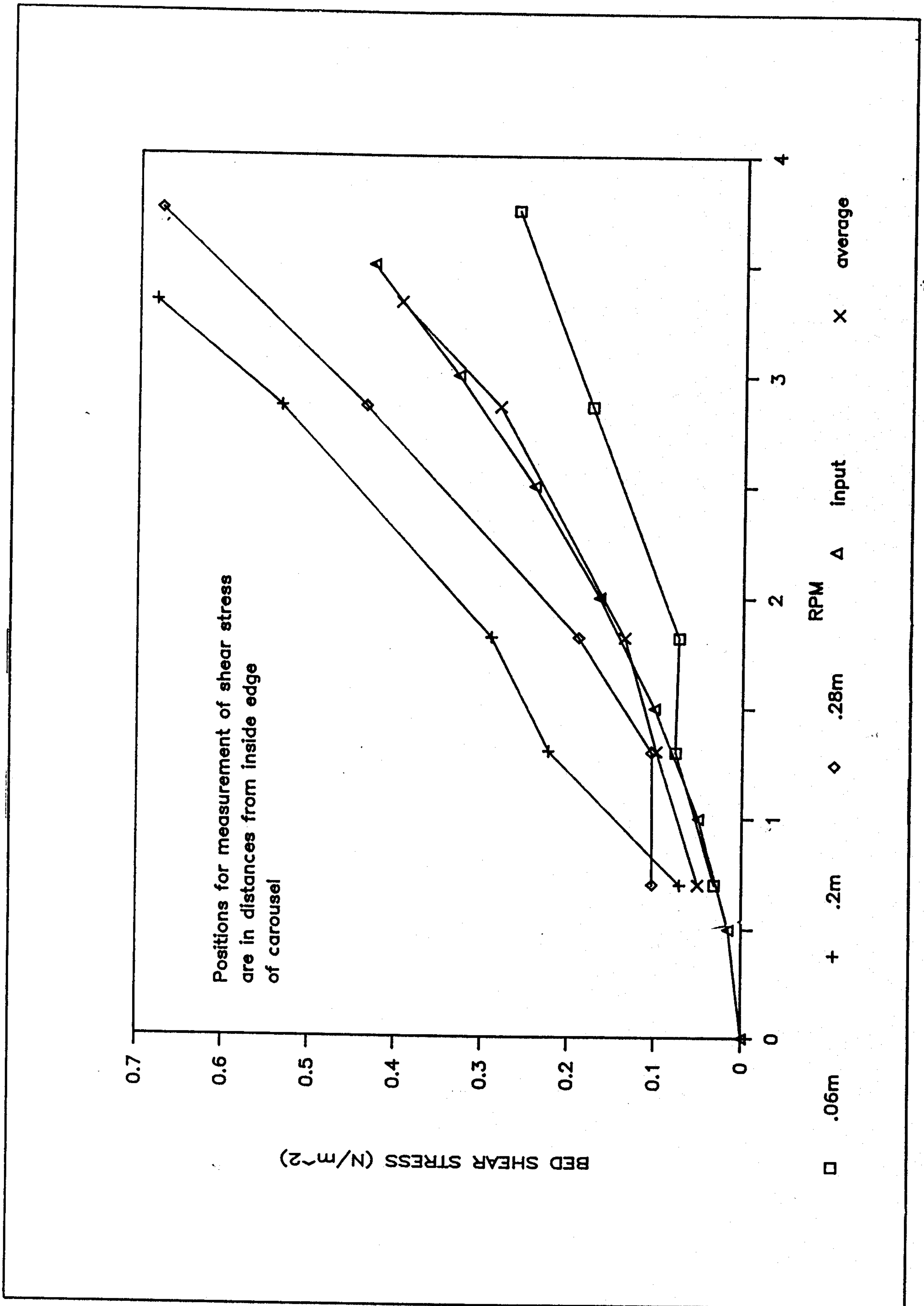

Fig 2 Bed shear stresses in carousel

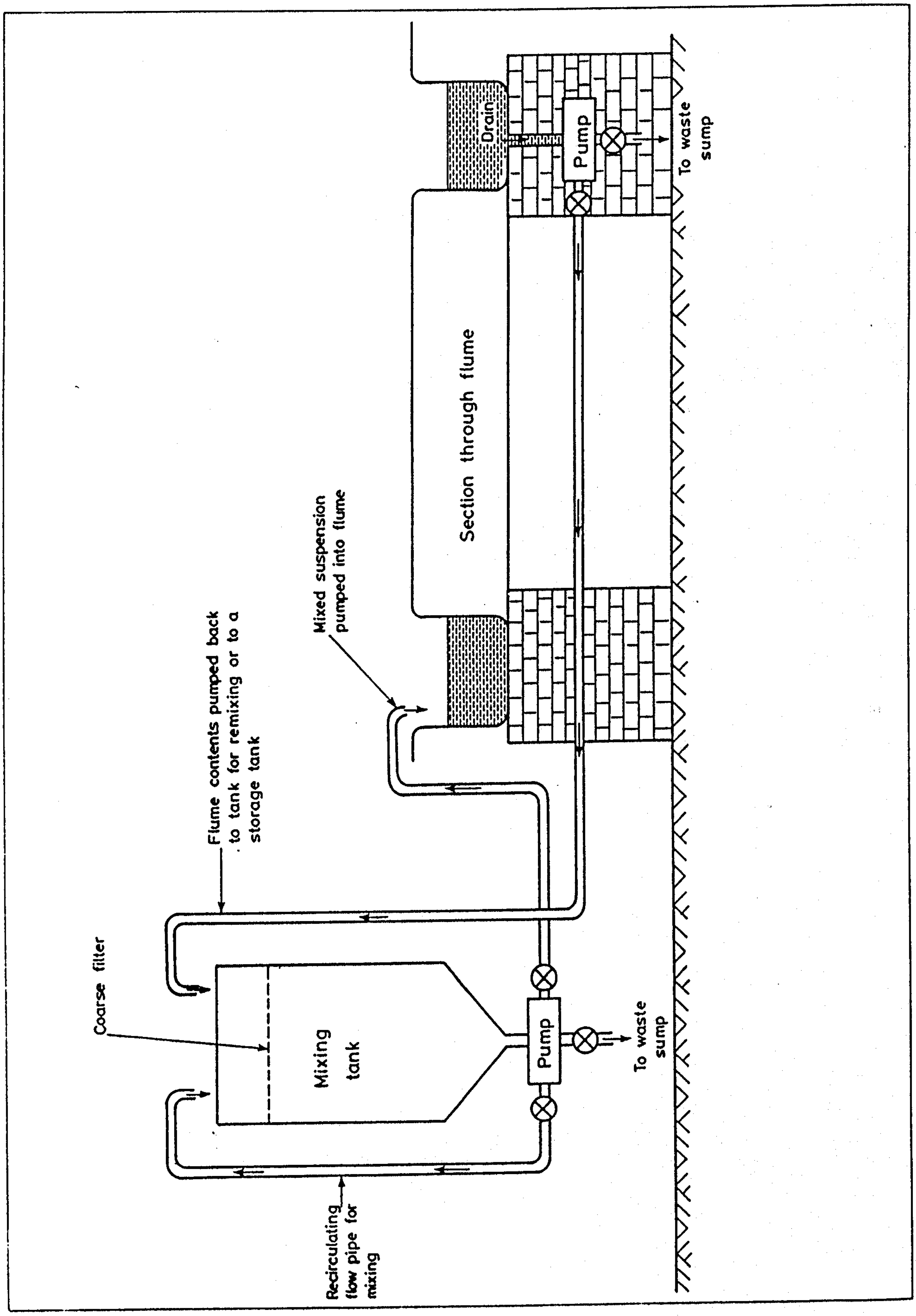

Fig 3 Filling and emptying system

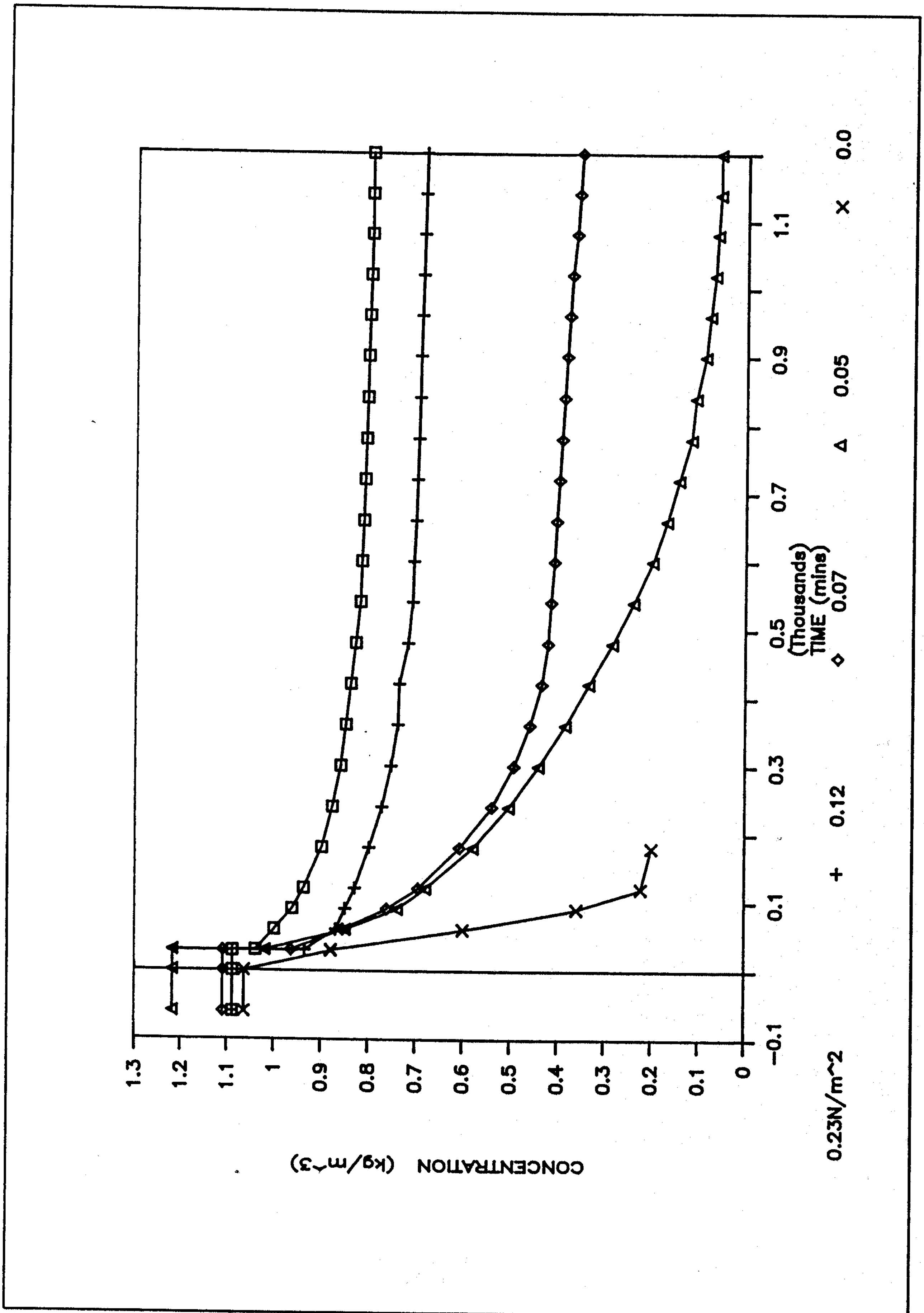

Fig 4 Typical carousel data

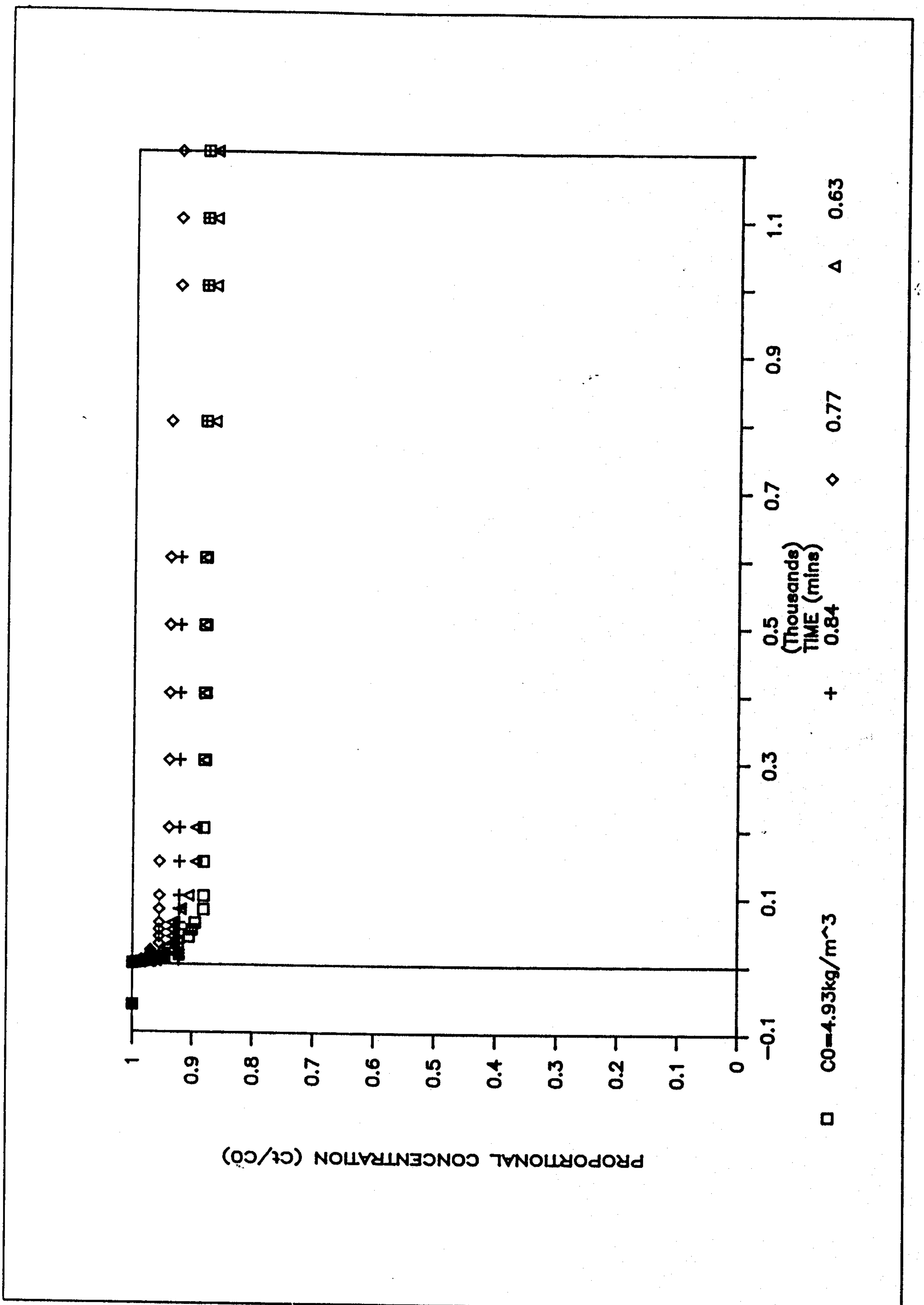

Fig 5 Proportional settling: bed shear stress = 0.36N/m↑2

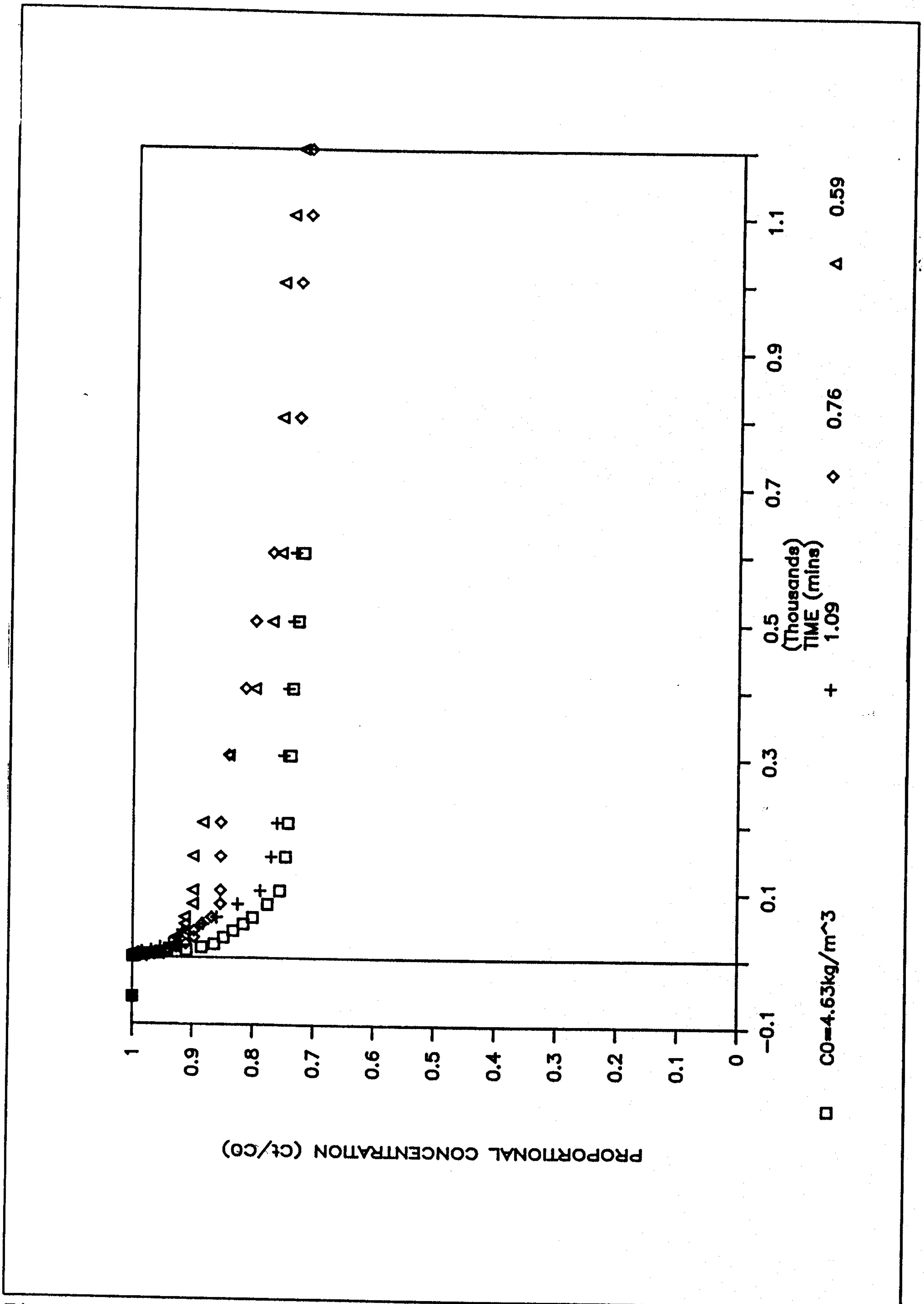

Fig 6   Proportional settling: bed shear stress = 0.23N/m↑2

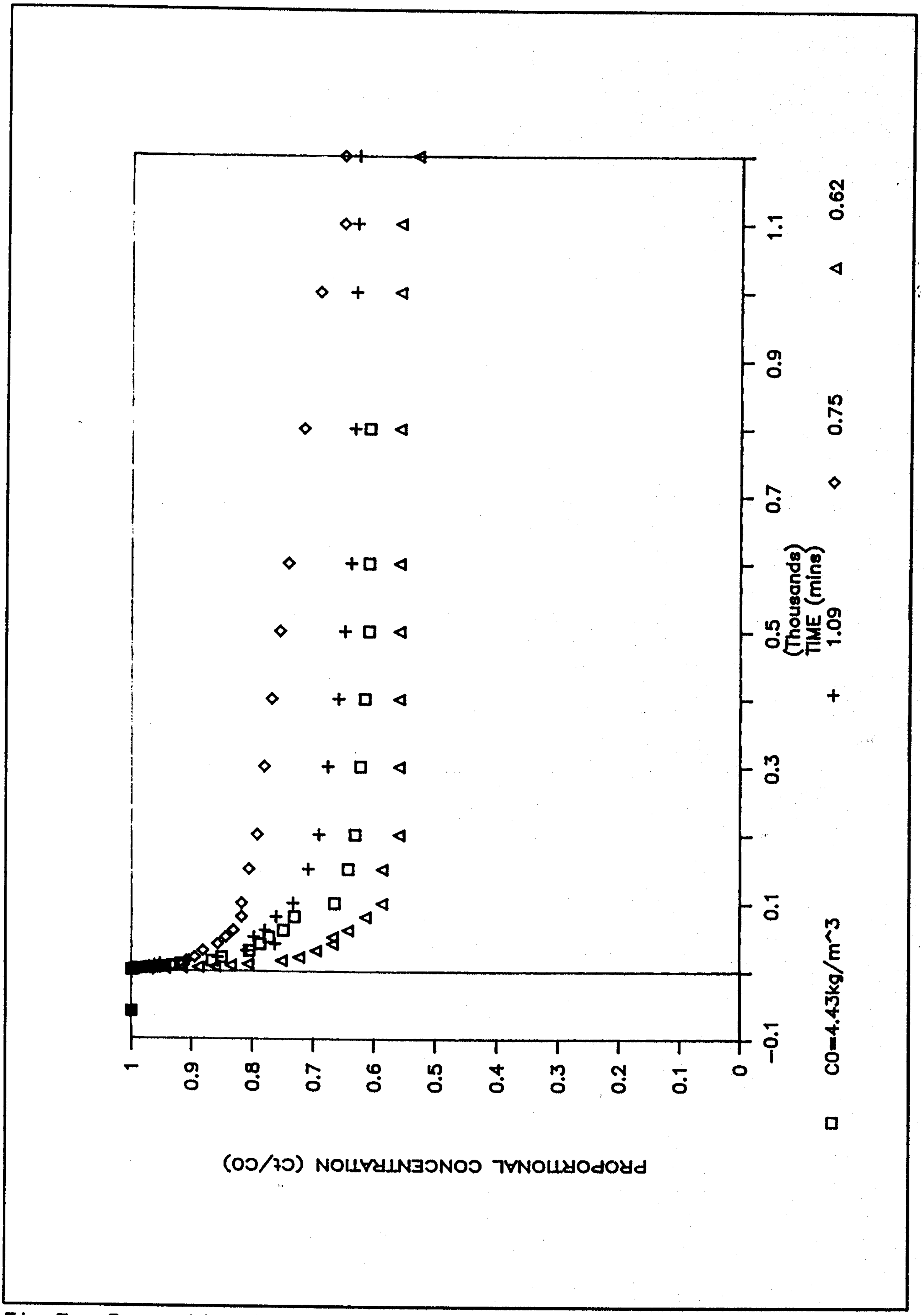

Fig 7 Proportional settling: bed shear stress = 0.12N/m↑2

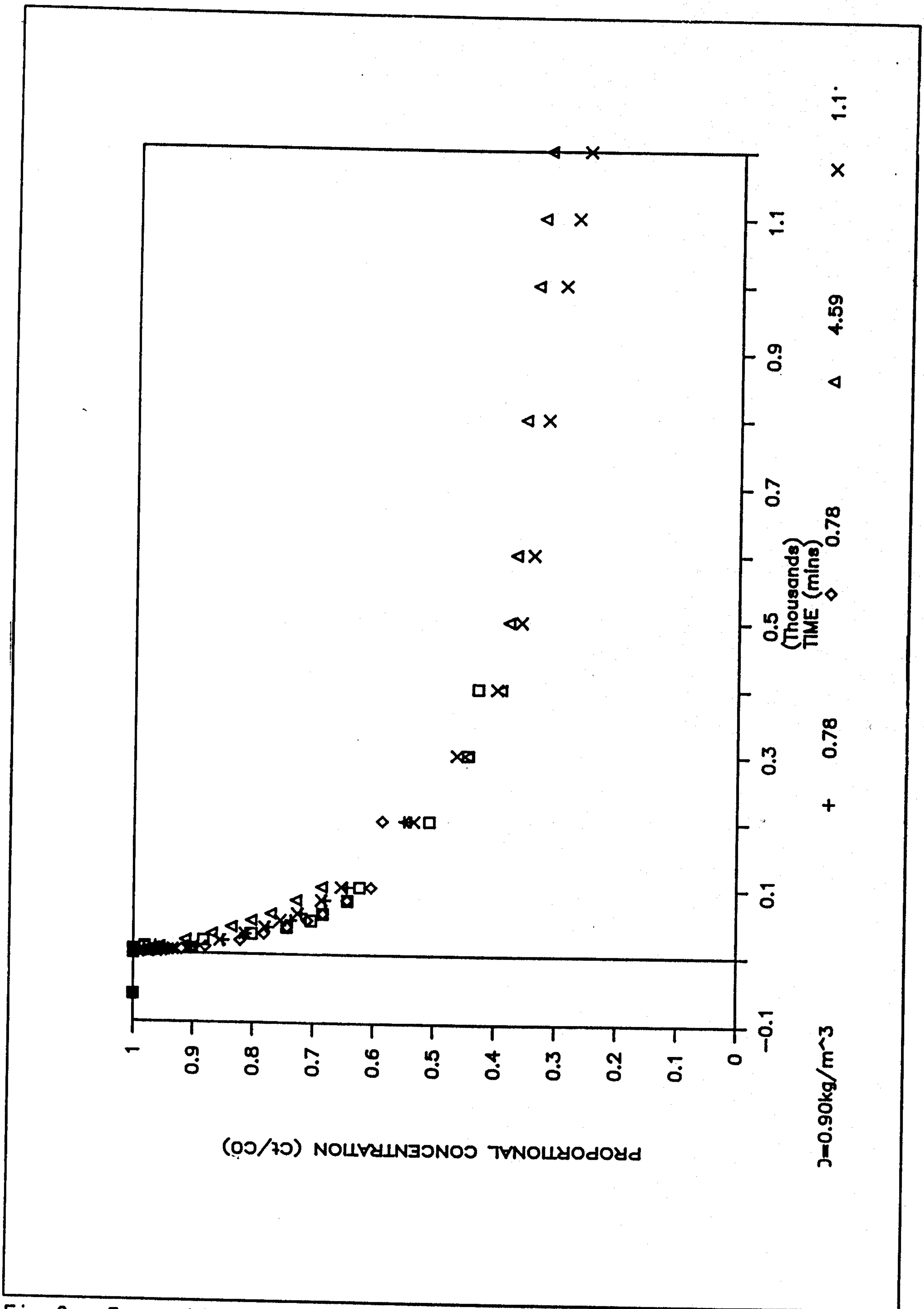

Fig 8 Proportional settling: bed shear stress = 0.07N/m↑2

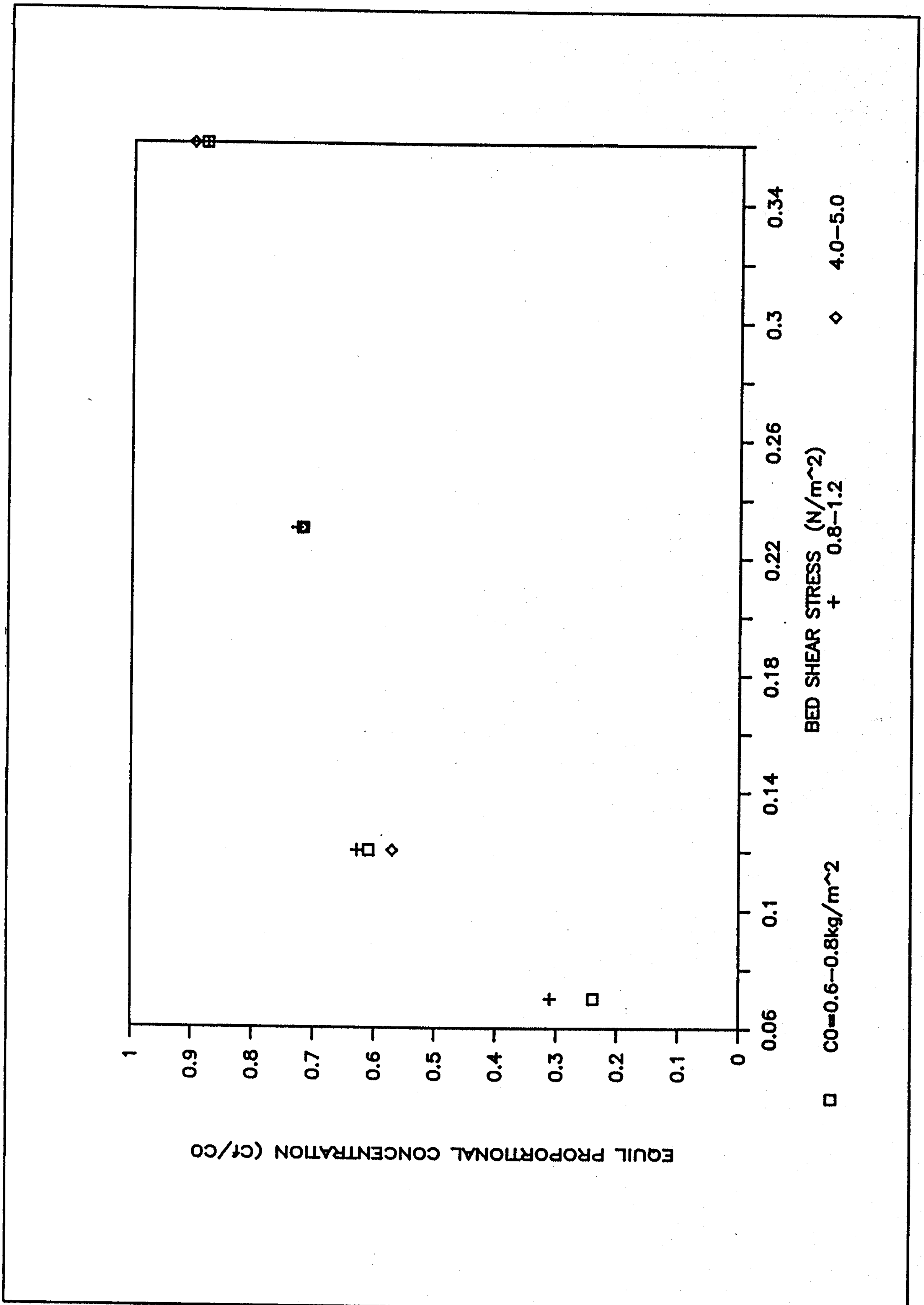

Fig 9 Equilibruim proportional concentration with bed shear stress

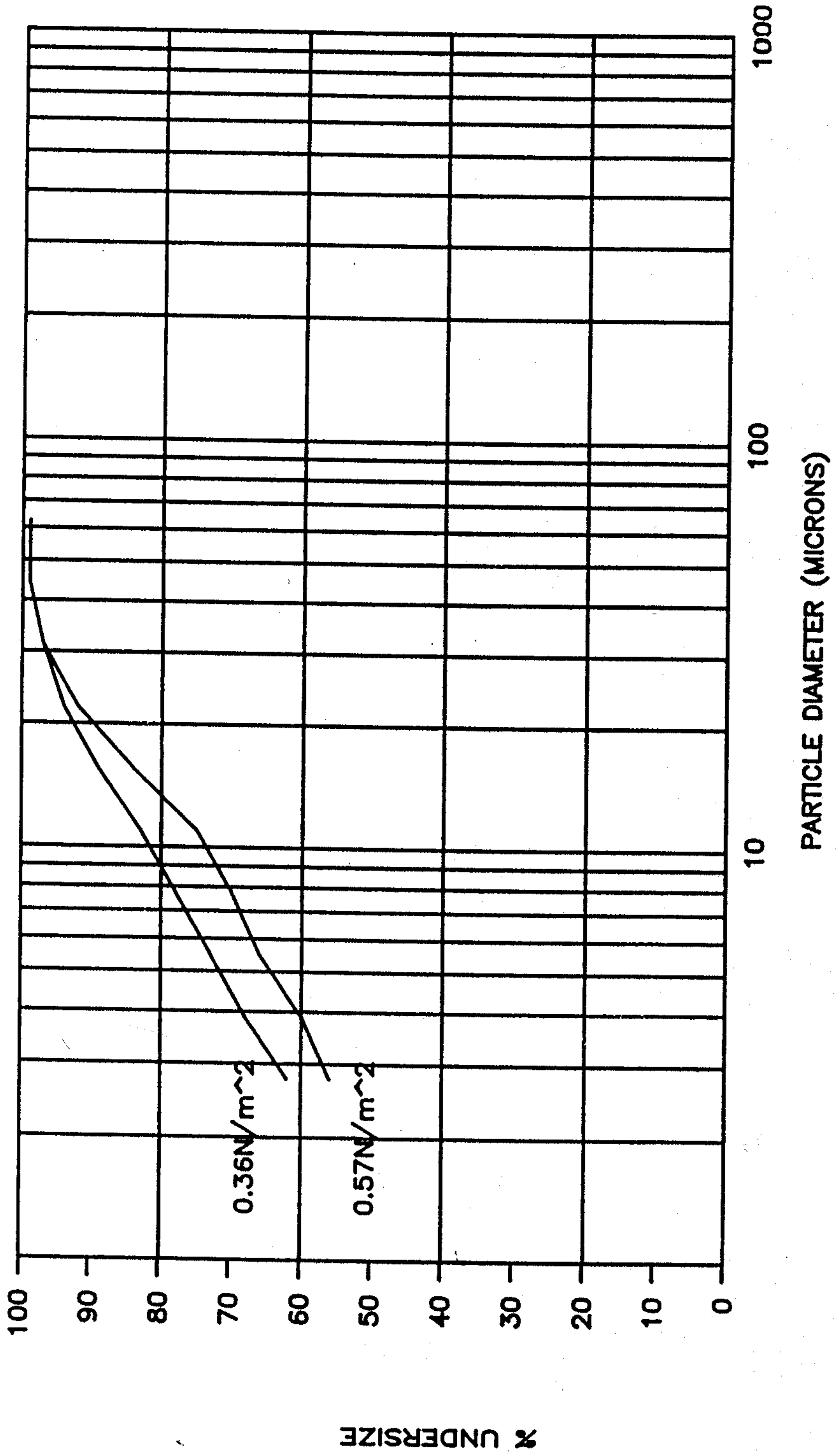

Fig 10 Primary particle size distributions: C0 = 0.633kg/m↑3, tor(b) = 0.36N/m↑2

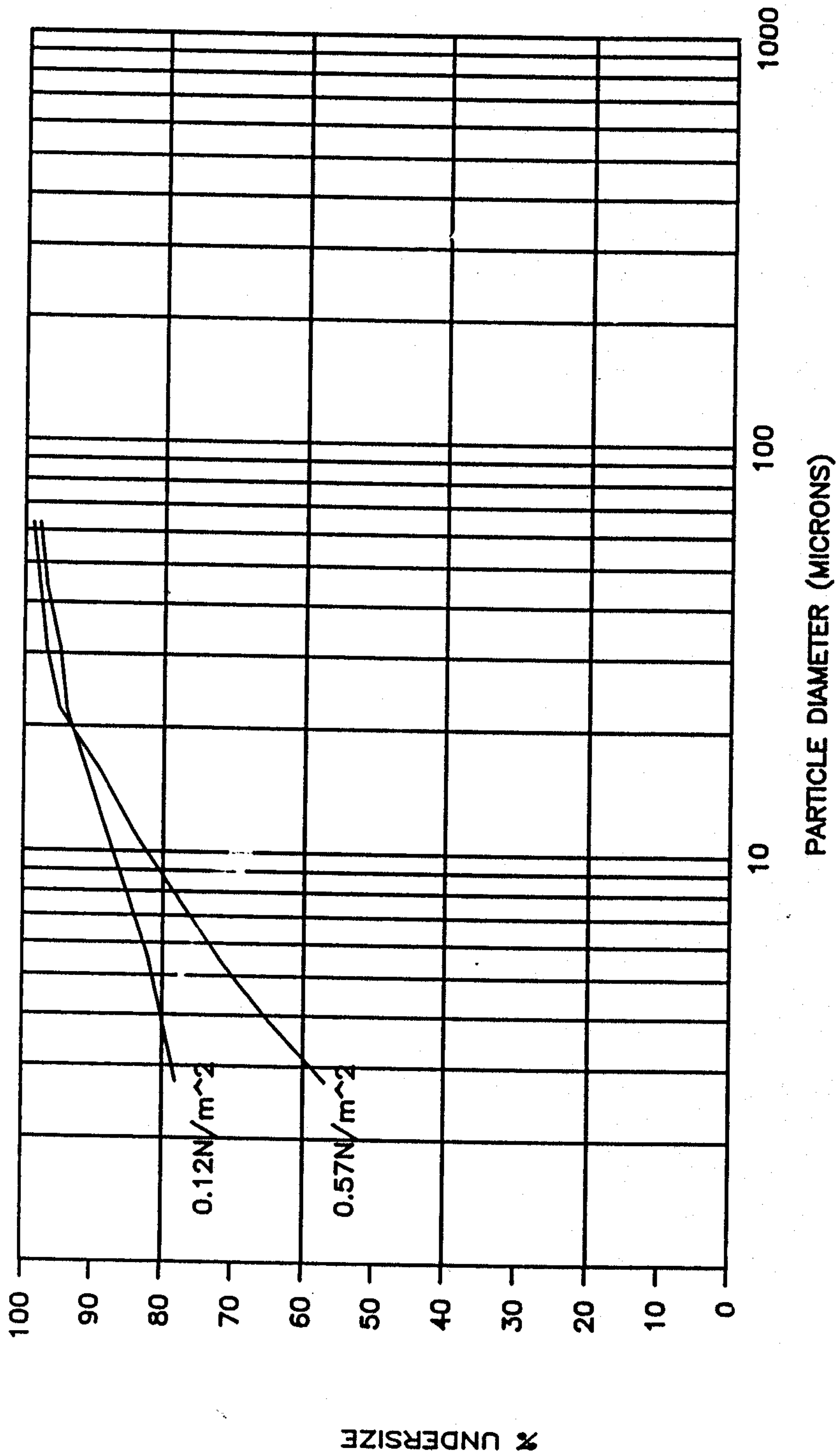

Fig 11 Primary particle size distributions: C0 = 0.622kg/m↑3, tor(b) = 0.12N/m↑2

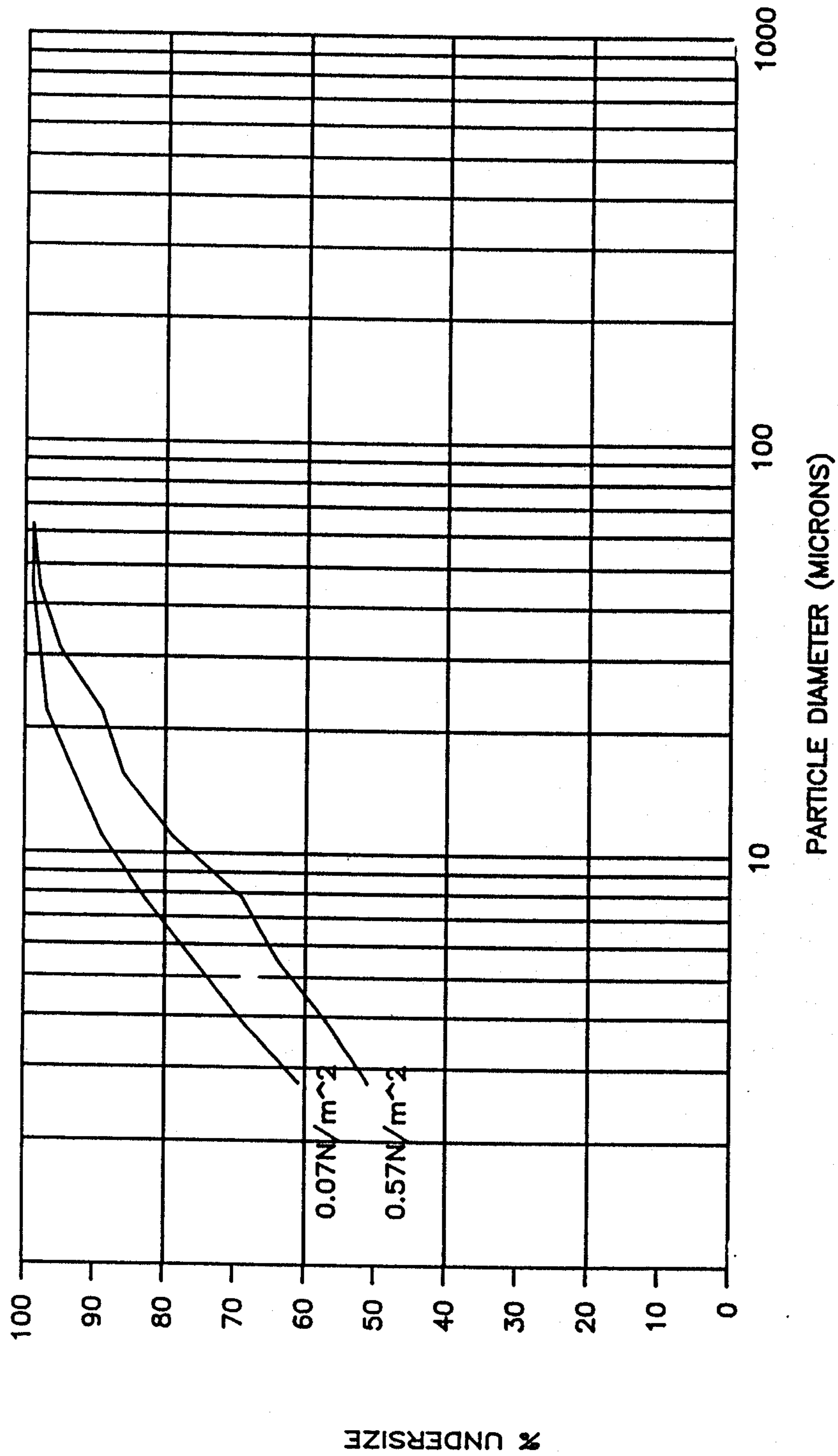

Fig 12 Primary particle size distributions: C0 = 1.141kg/m↑3, tor(b) = 0.07N/m↑2

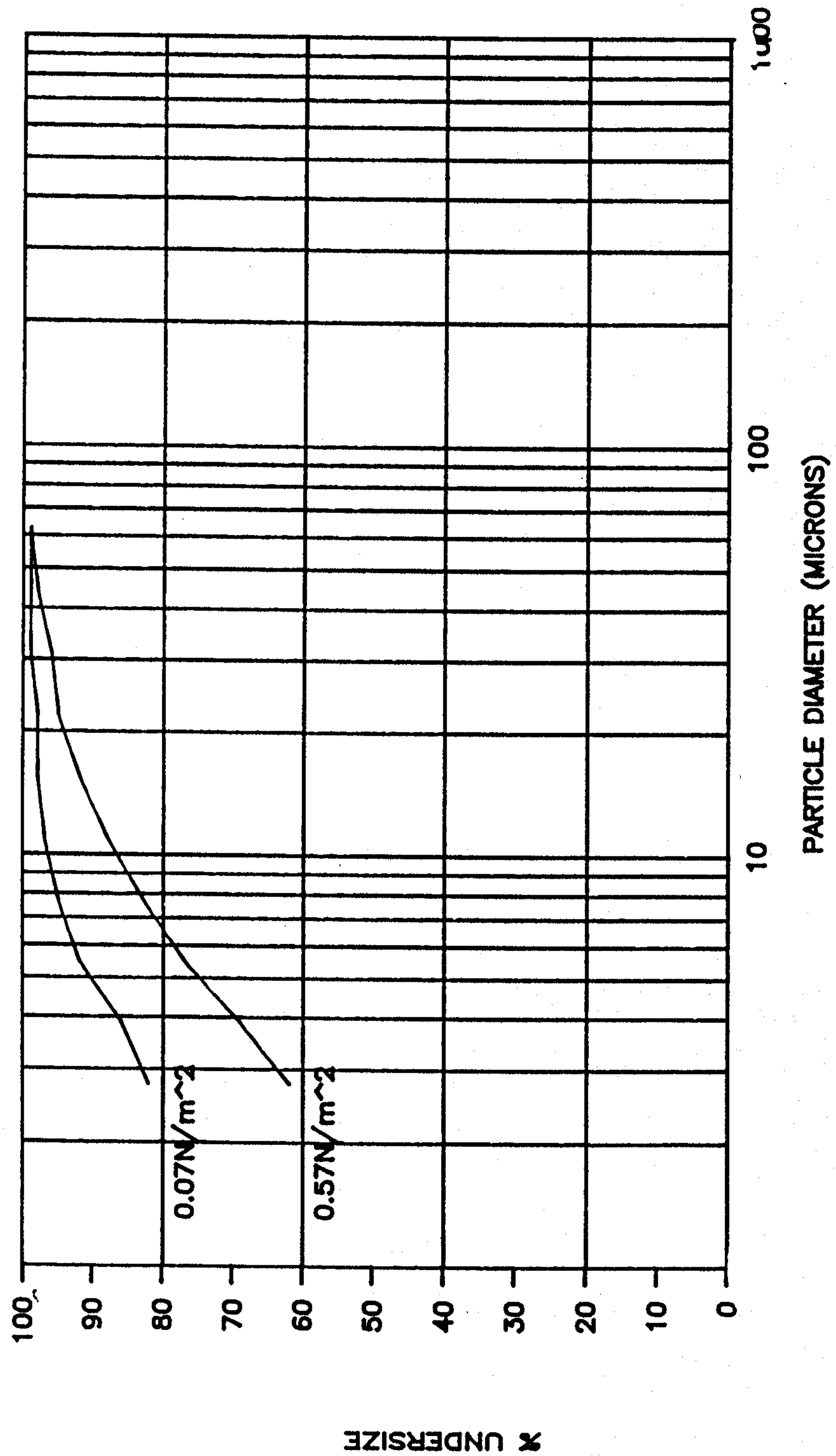

Fig 13 Primary particle size distributions: C0 = 4.586kg/m↑3, tor(b) = 0.07N/m↑2

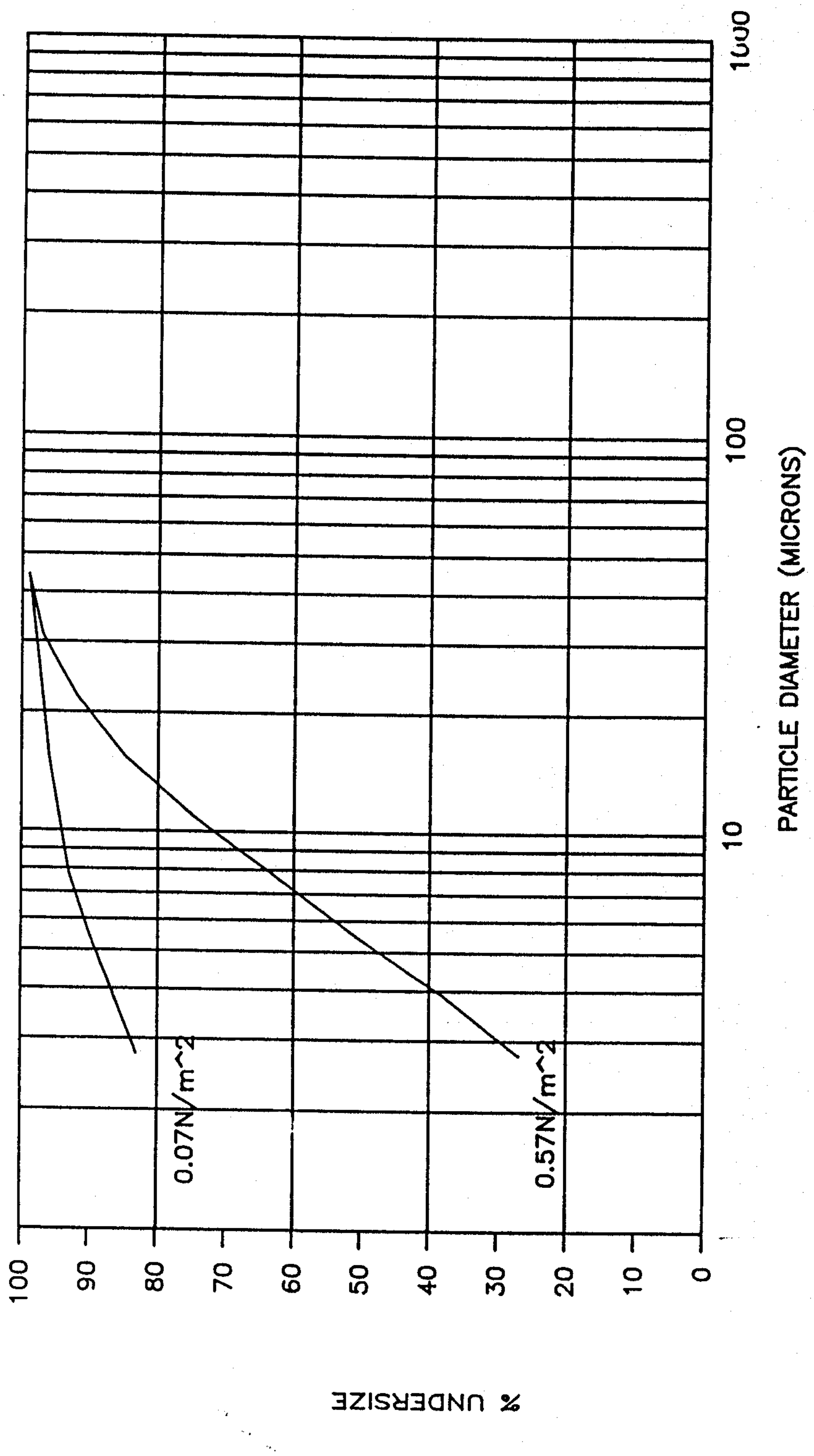

Fig 14 Primary particle size distributions: no salinity

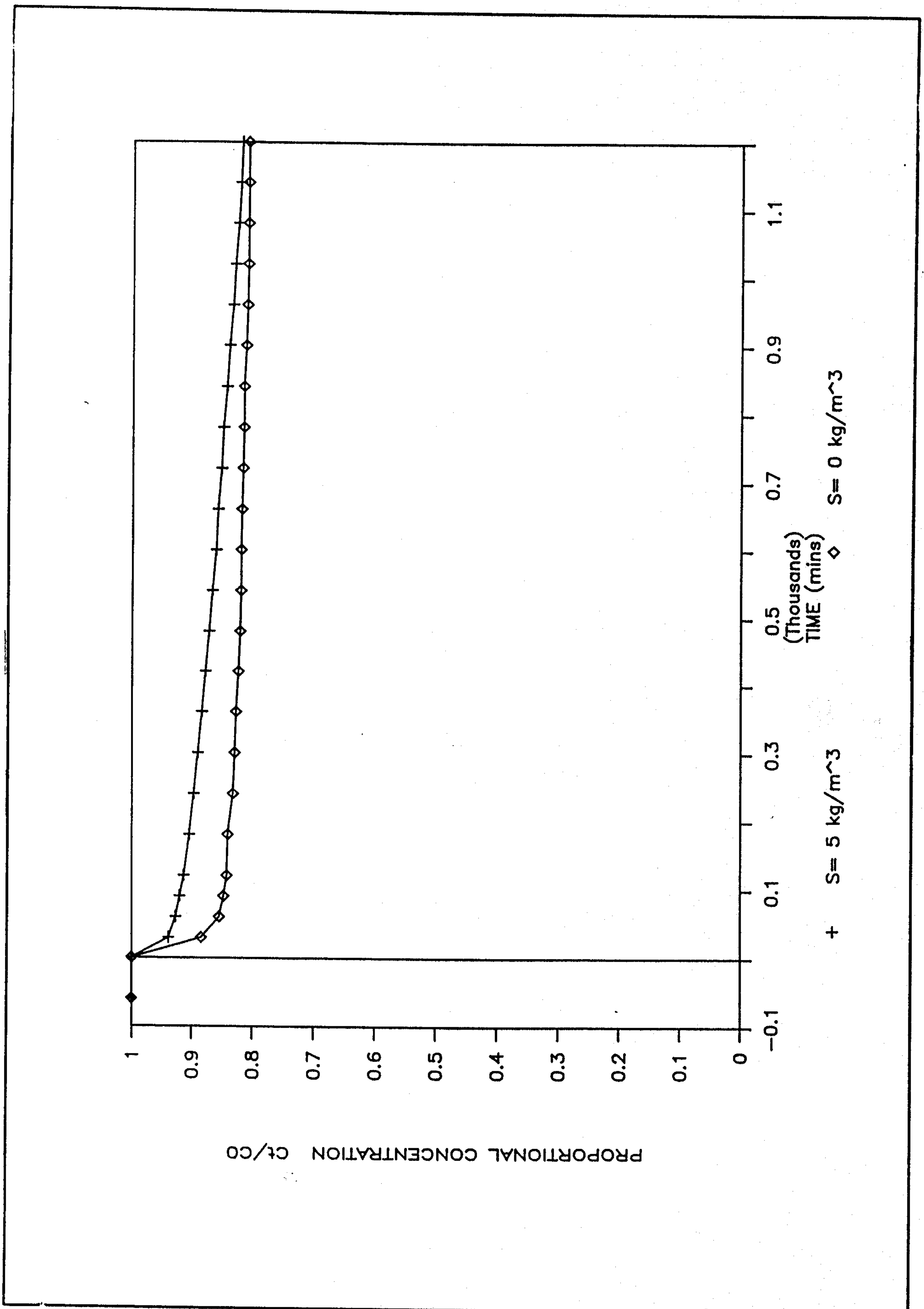

Fig 15 Effect of salinity: bed shear stress = 0.36N/m↑2:
CO = approx 1.0kg/m↑3

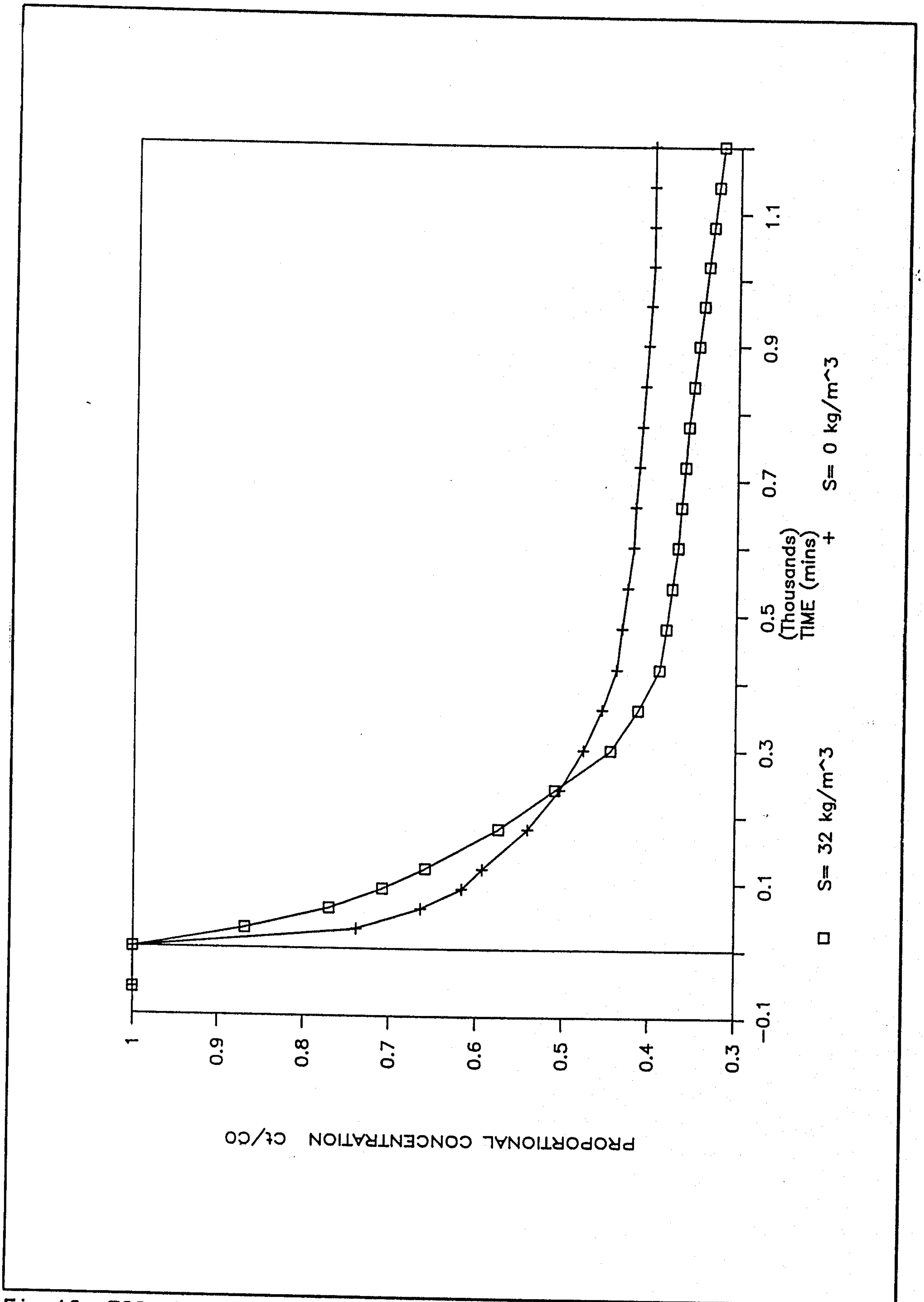

Fig 16 Effect of salinity: bed shear stress = 0.07N/m↑2:
CO = approx 1.0kg/m↑3

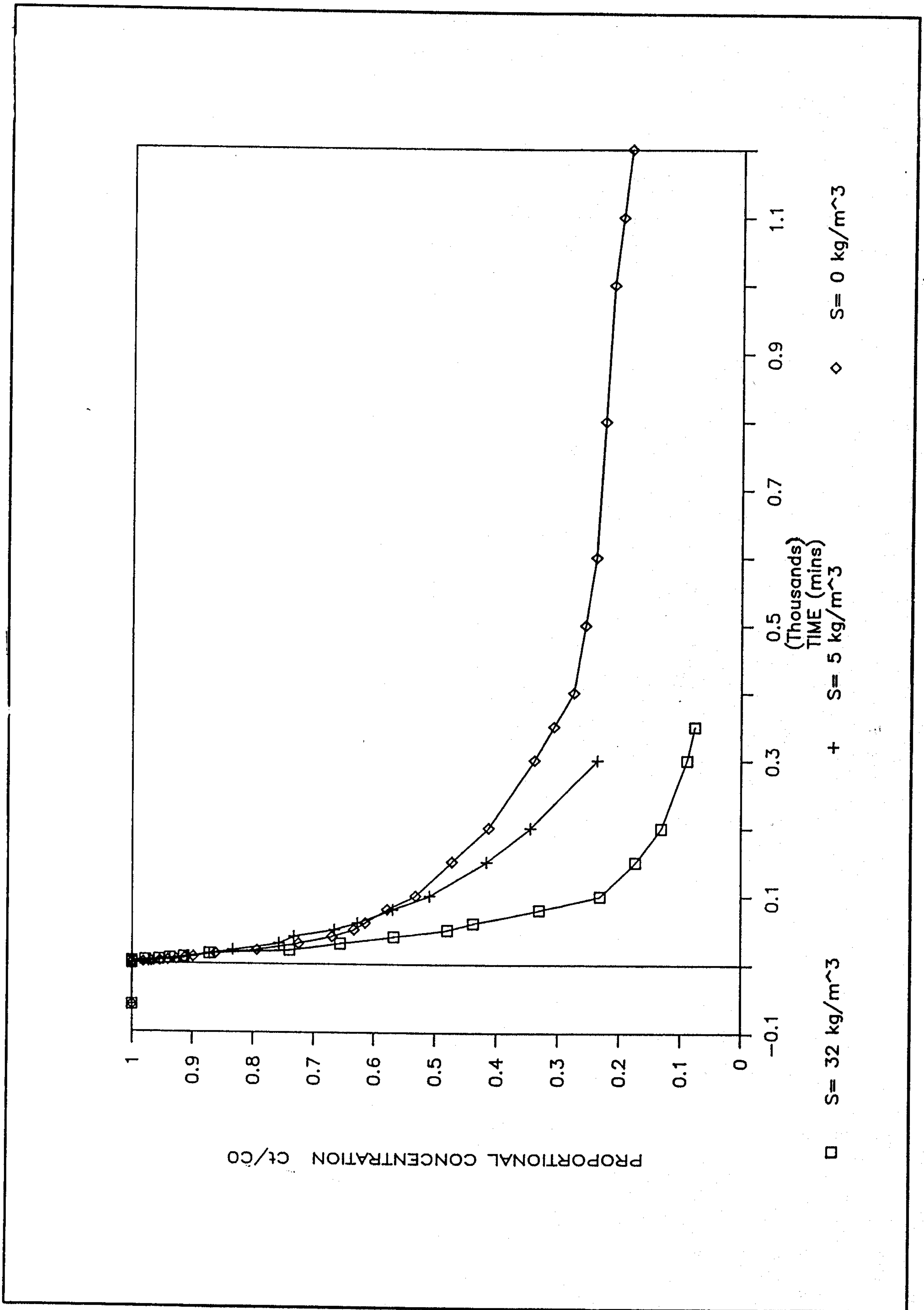

Fig 17 Effect of salinity: bed shear stress = 0.00N/m↑2:
CO = approx 1.0kg/m↑3

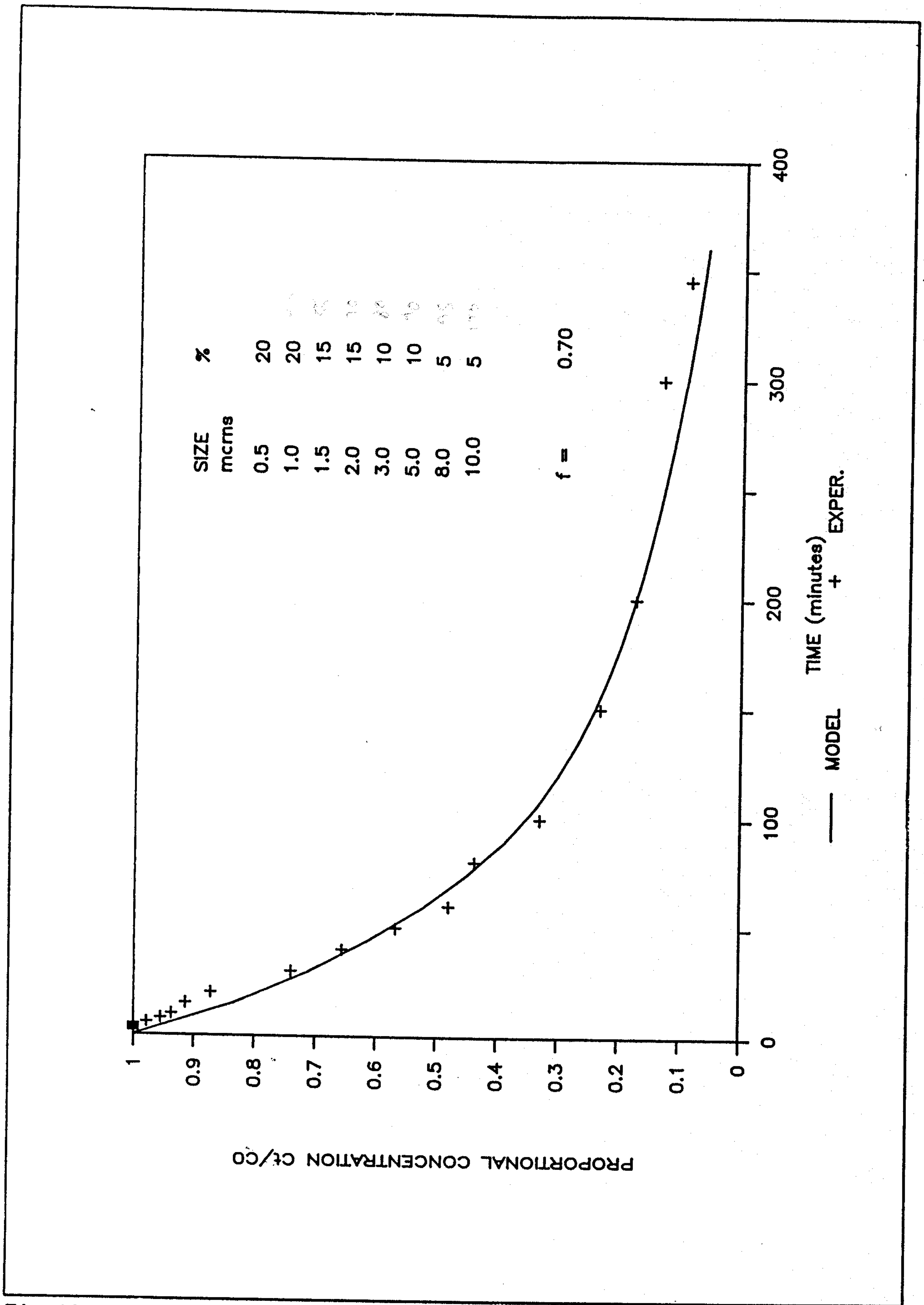

Fig 18 Quiescent settling test to determine flocculated settling velocity distribution

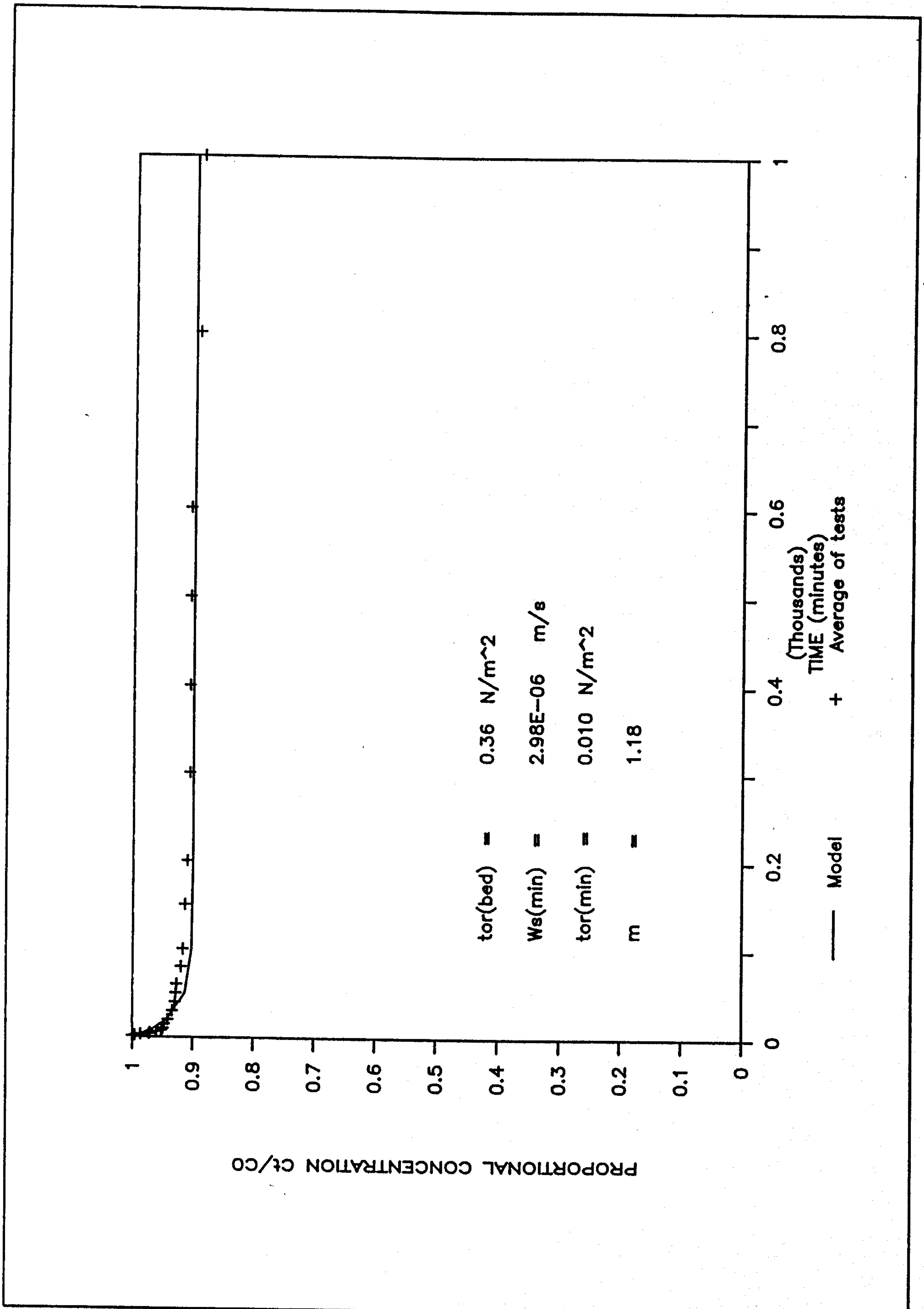

Fig 19 Calibration of tor(d1): bed shear stress = 0.36N/m↑2

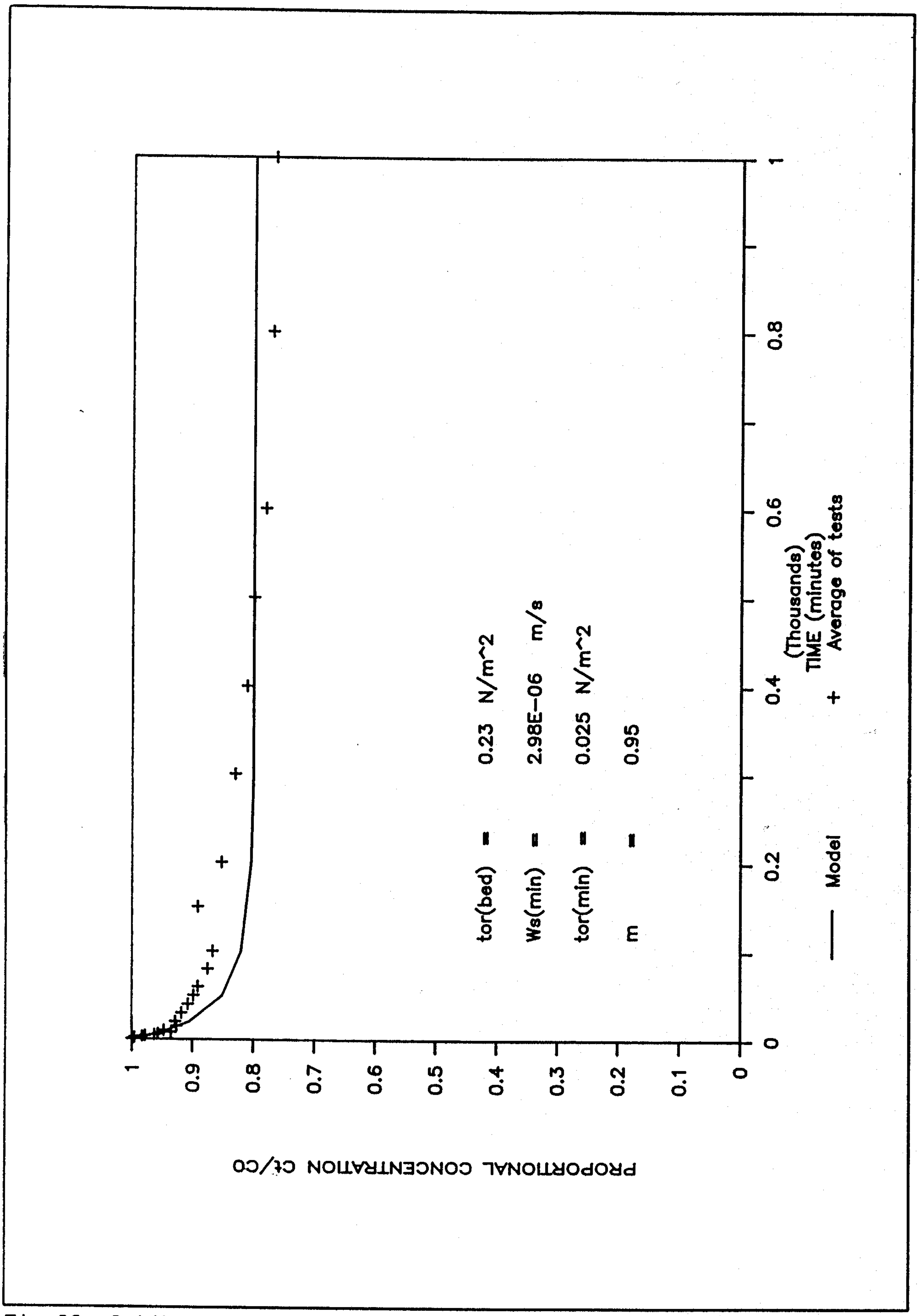

Fig 20 Calibration of tor(d1): bed shear stress = 0.23N/m↑2

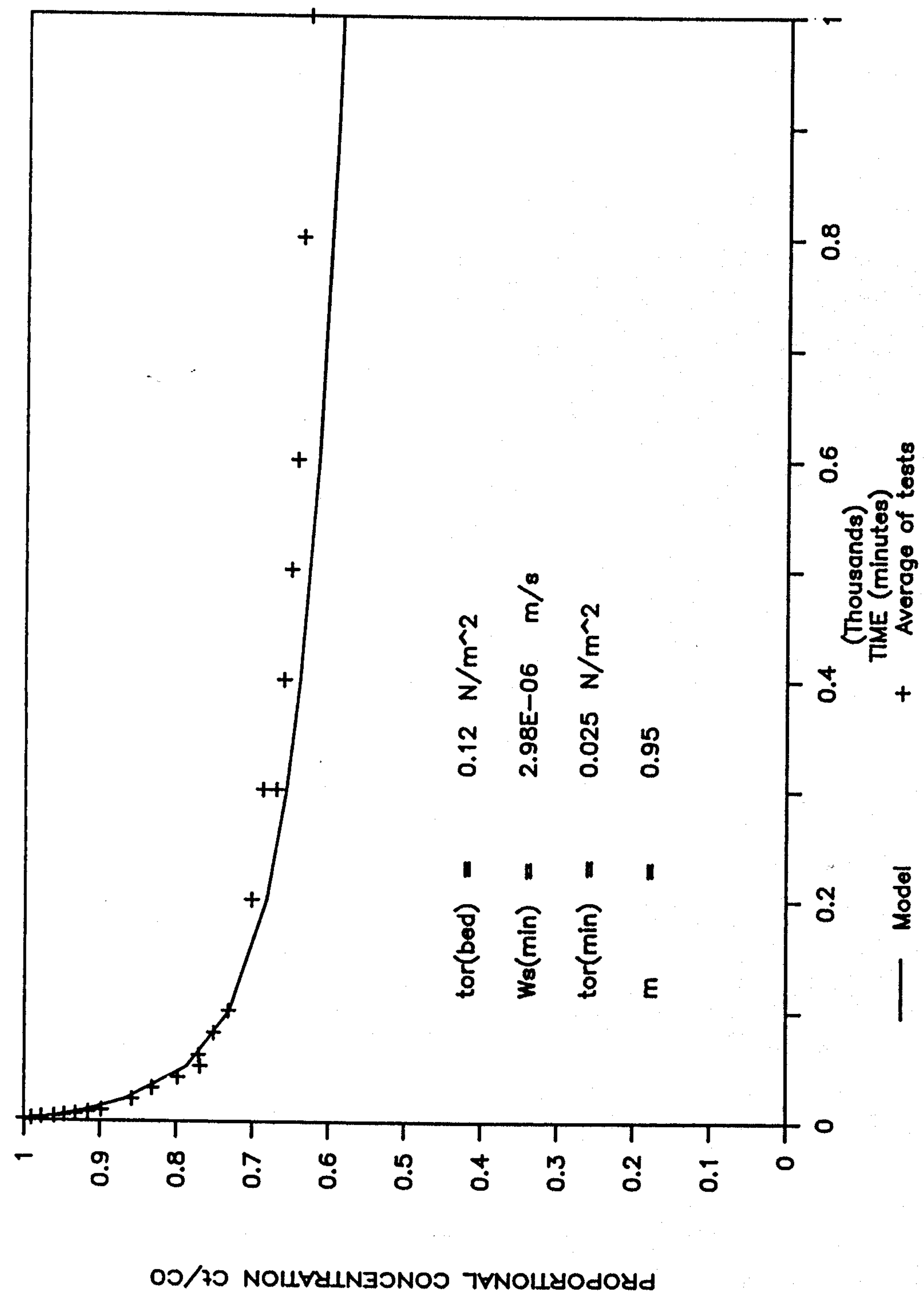

Fig 21 Calibration of tor(d1): bed shear stress = 0.12N/m↑2

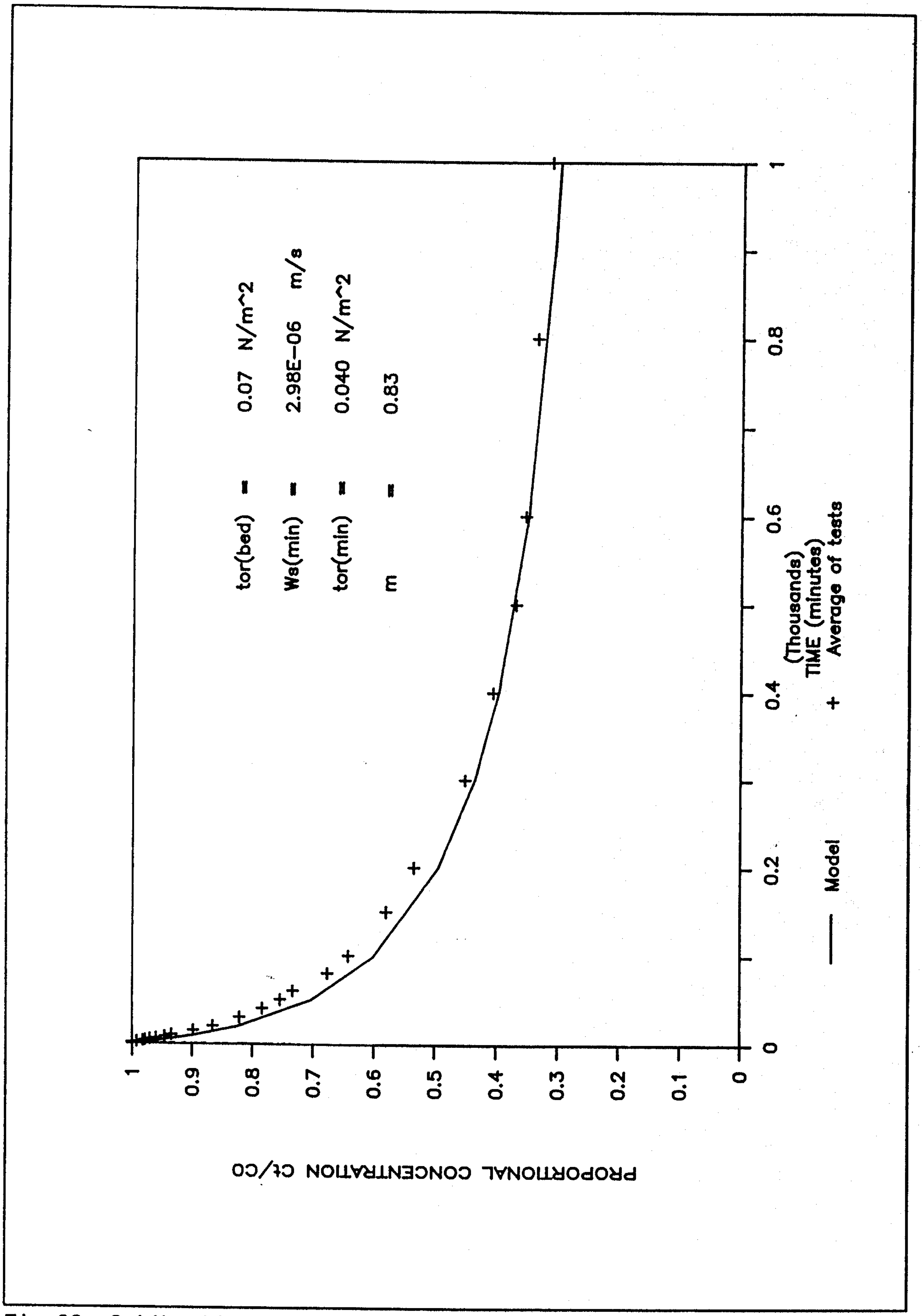

Fig 22 Calibration of tor(d1): bed shear stress = 0.07N/m↑2

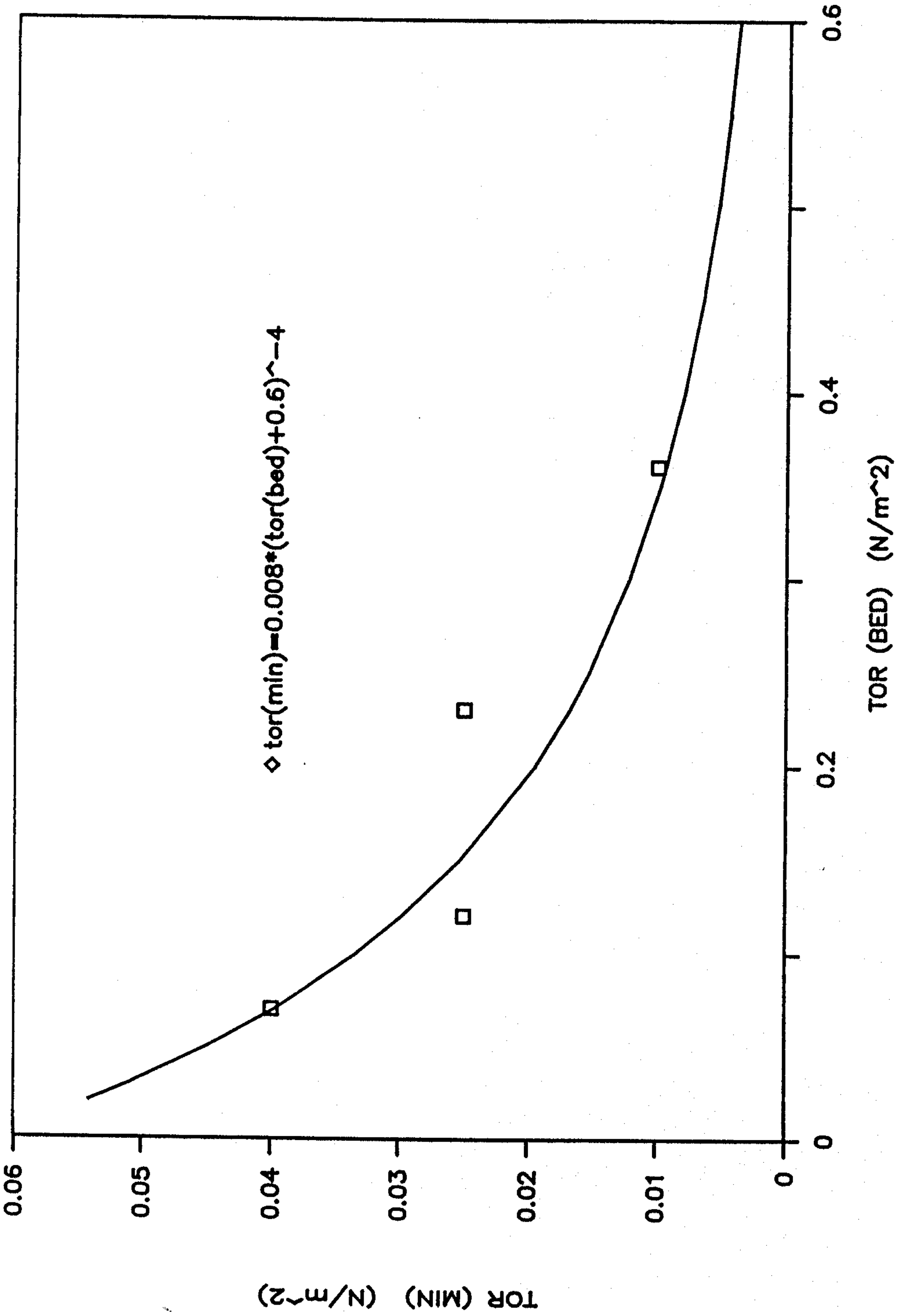

Fig 23 Characteristic shear stress tor(d1) with bed shear stress

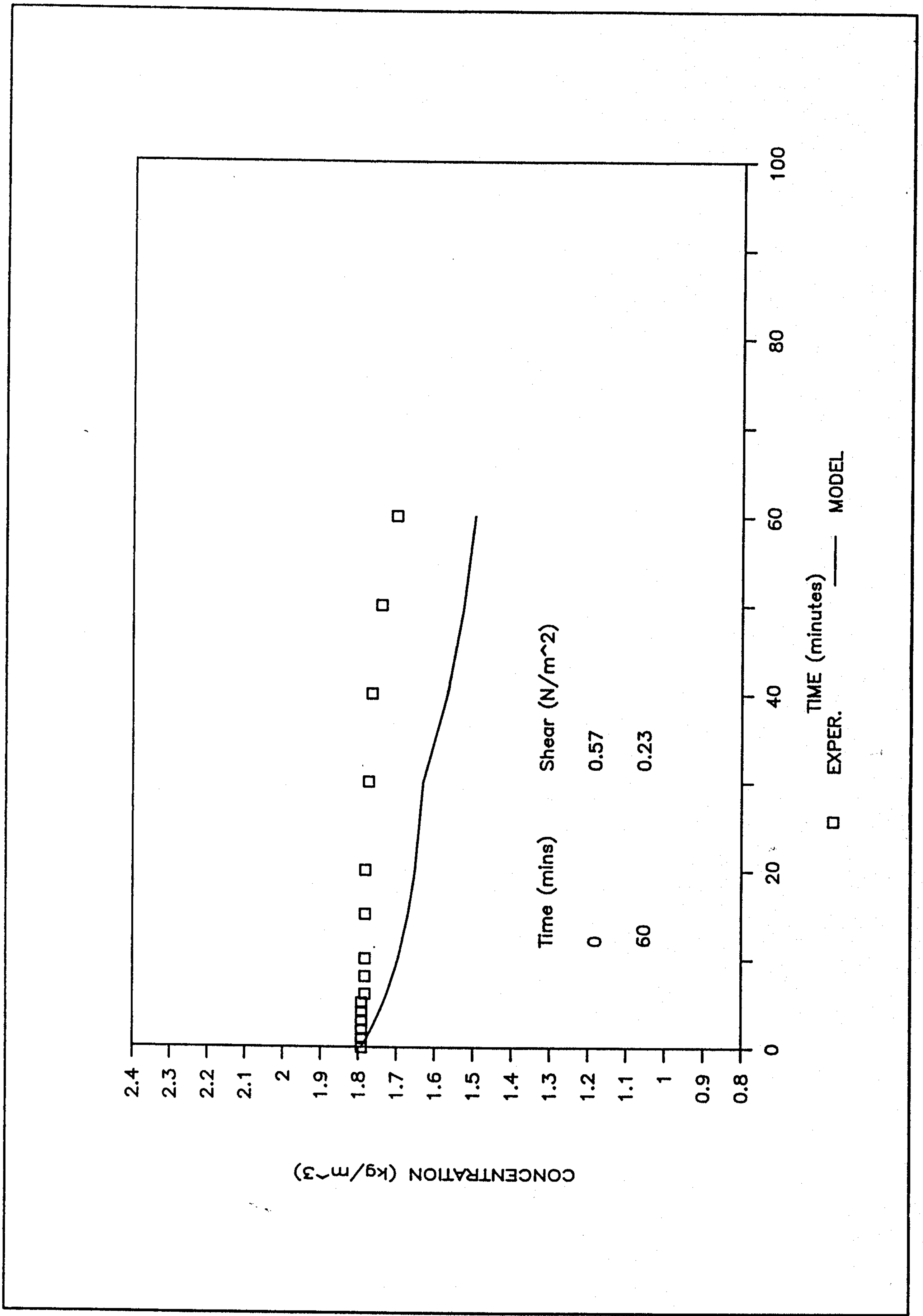

Fig 24 Model prediction Test C1: tor(b)(60mins) = 0.23N/m↑2, C0 = 1.79kg/m↑3

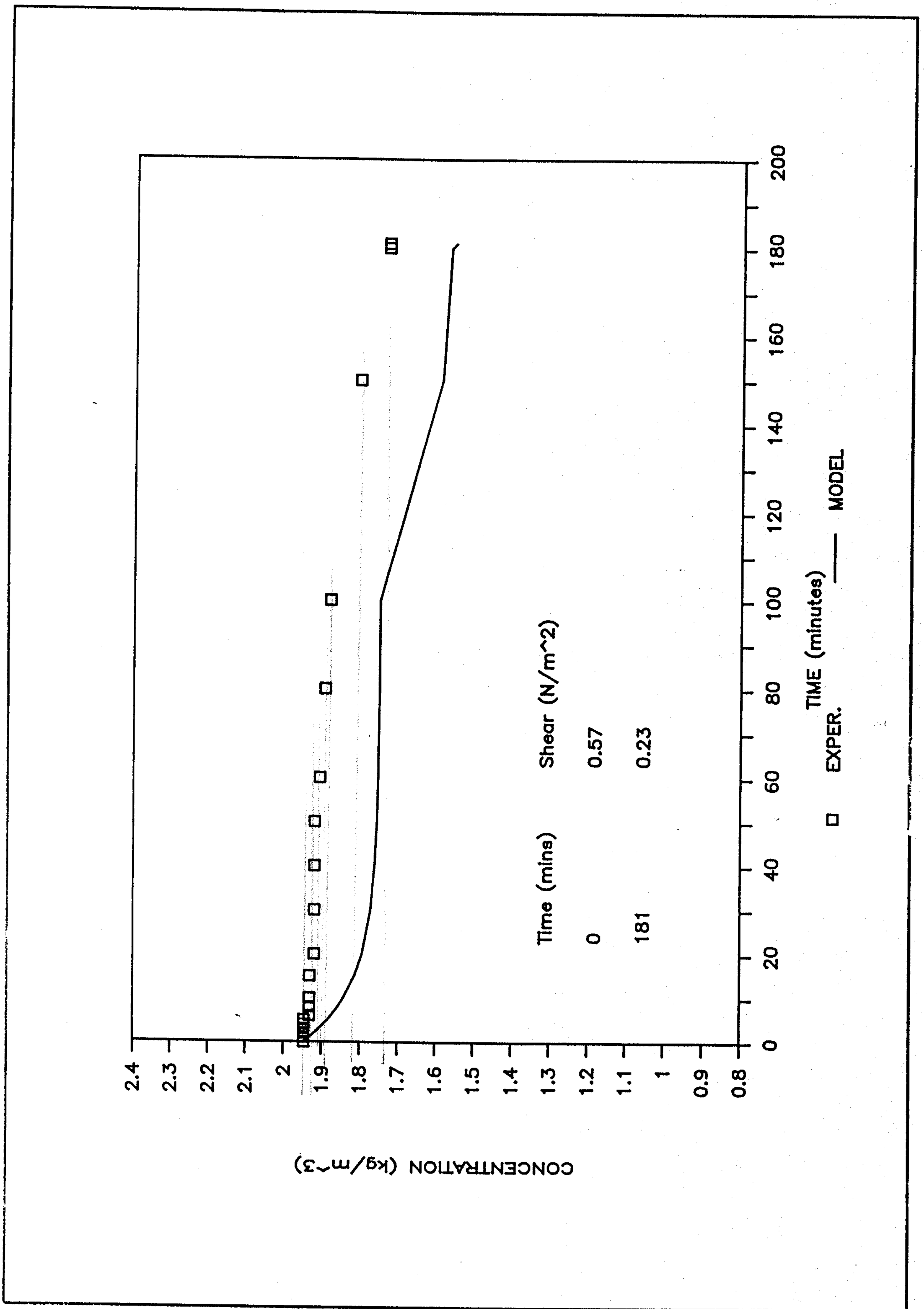

Fig 25 Model prediction Test C2: tor(b)(180mins) = 0.23N/m↑2,
CO = 1.95kg/m↑3

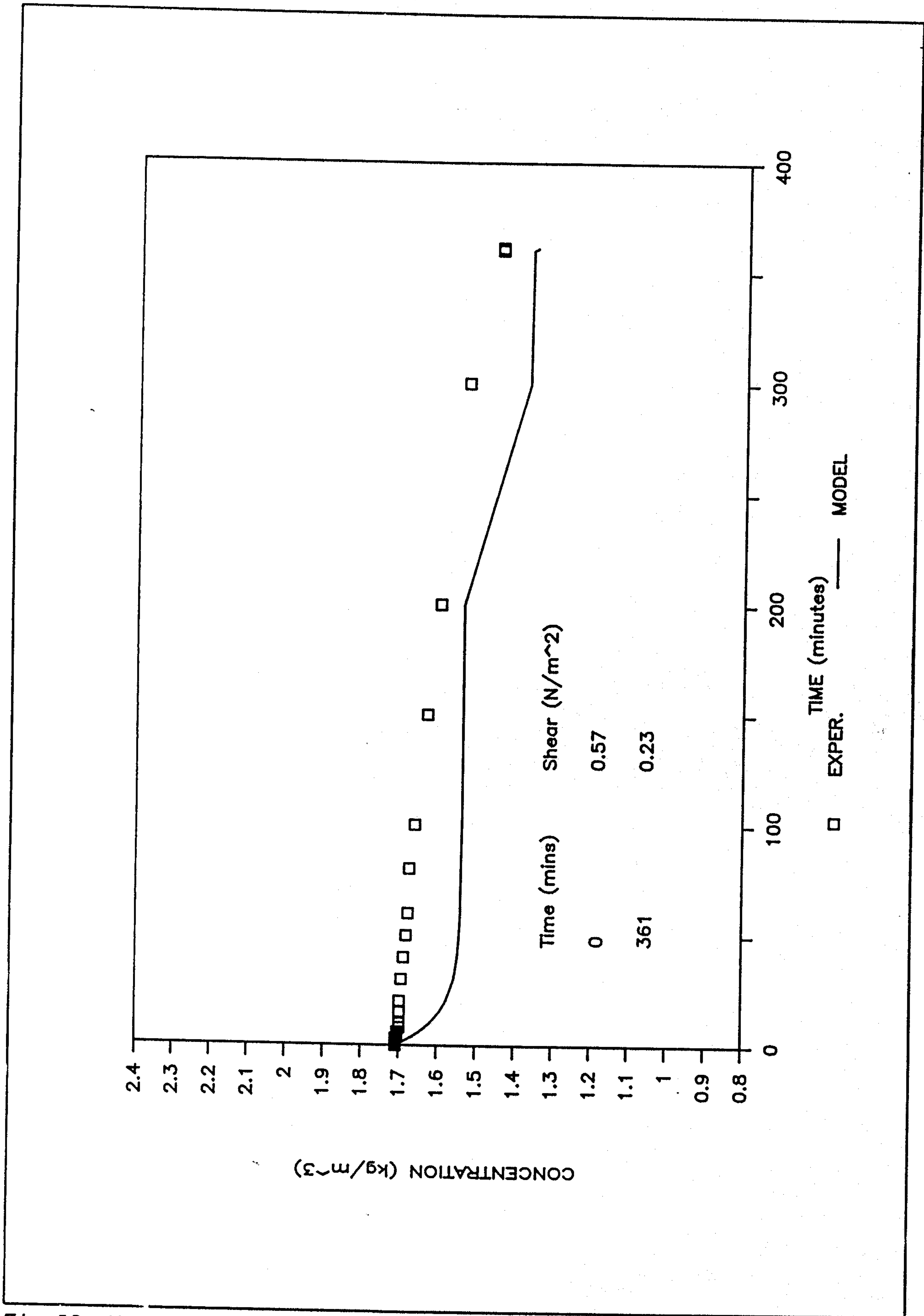

Fig 26 Model prediction Test C3: tor(b)(360mins) = 0.23N/m↑2,
C0 = 1.72Kg/m↑3

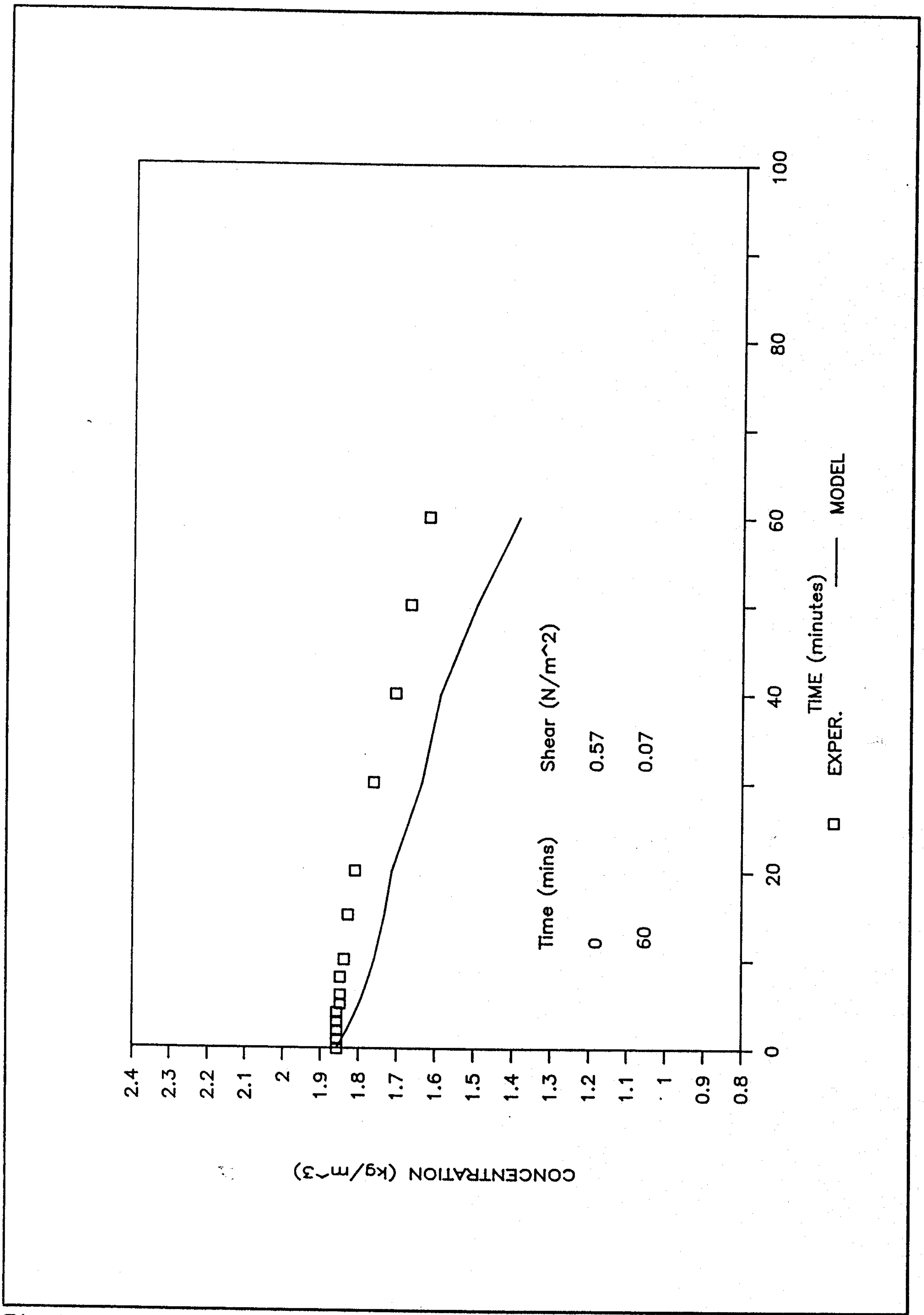

Fig 27 Model prediction Test C4: tor(b)(60mins) = 0.07N/m↑2,
C0 = 1.86kg/m↑3

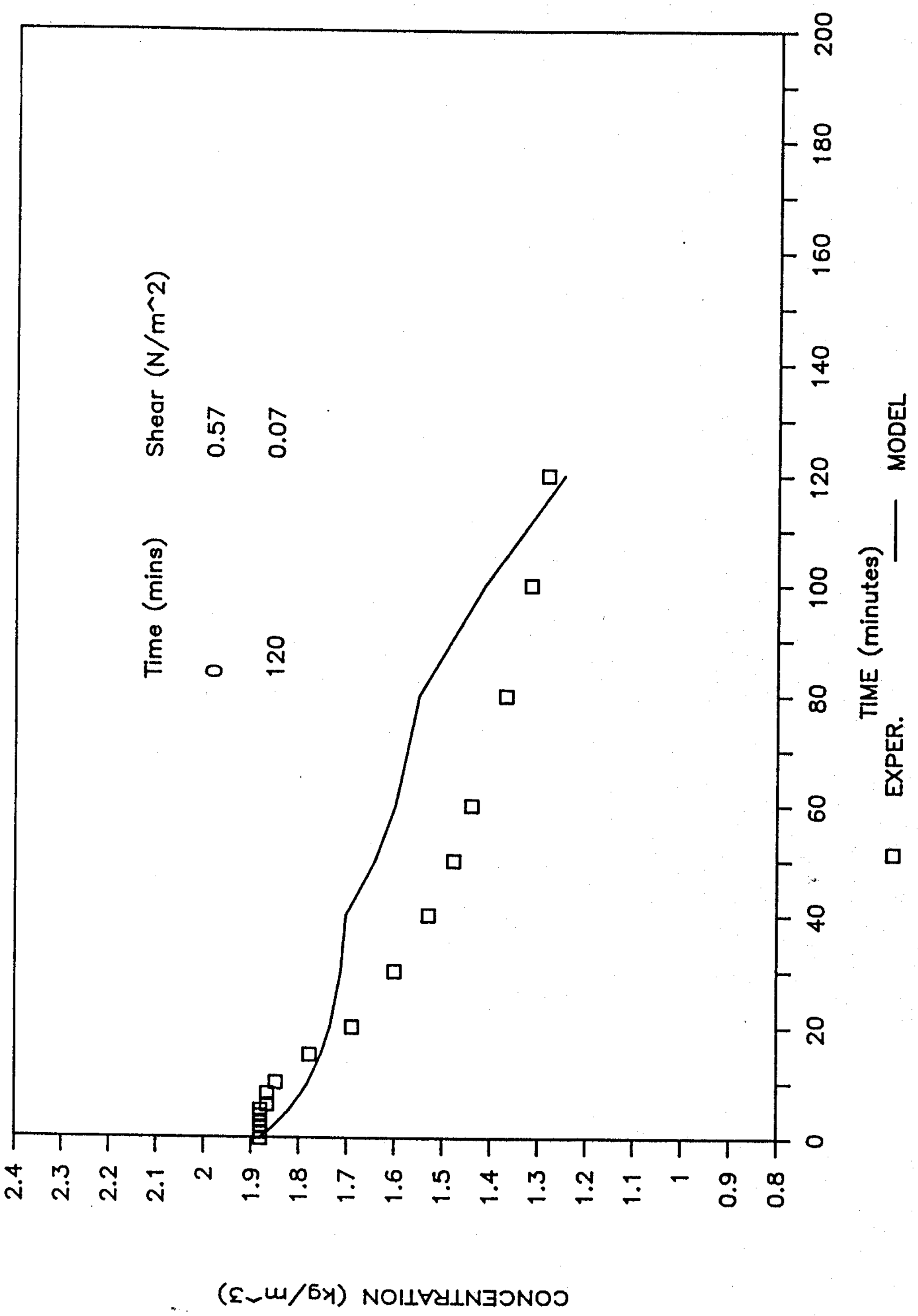

Fig 28 Model prediction Test C5: tor(b)(120mins) = 0.07N/m↑2,
C0 = 1.88kg/m↑3

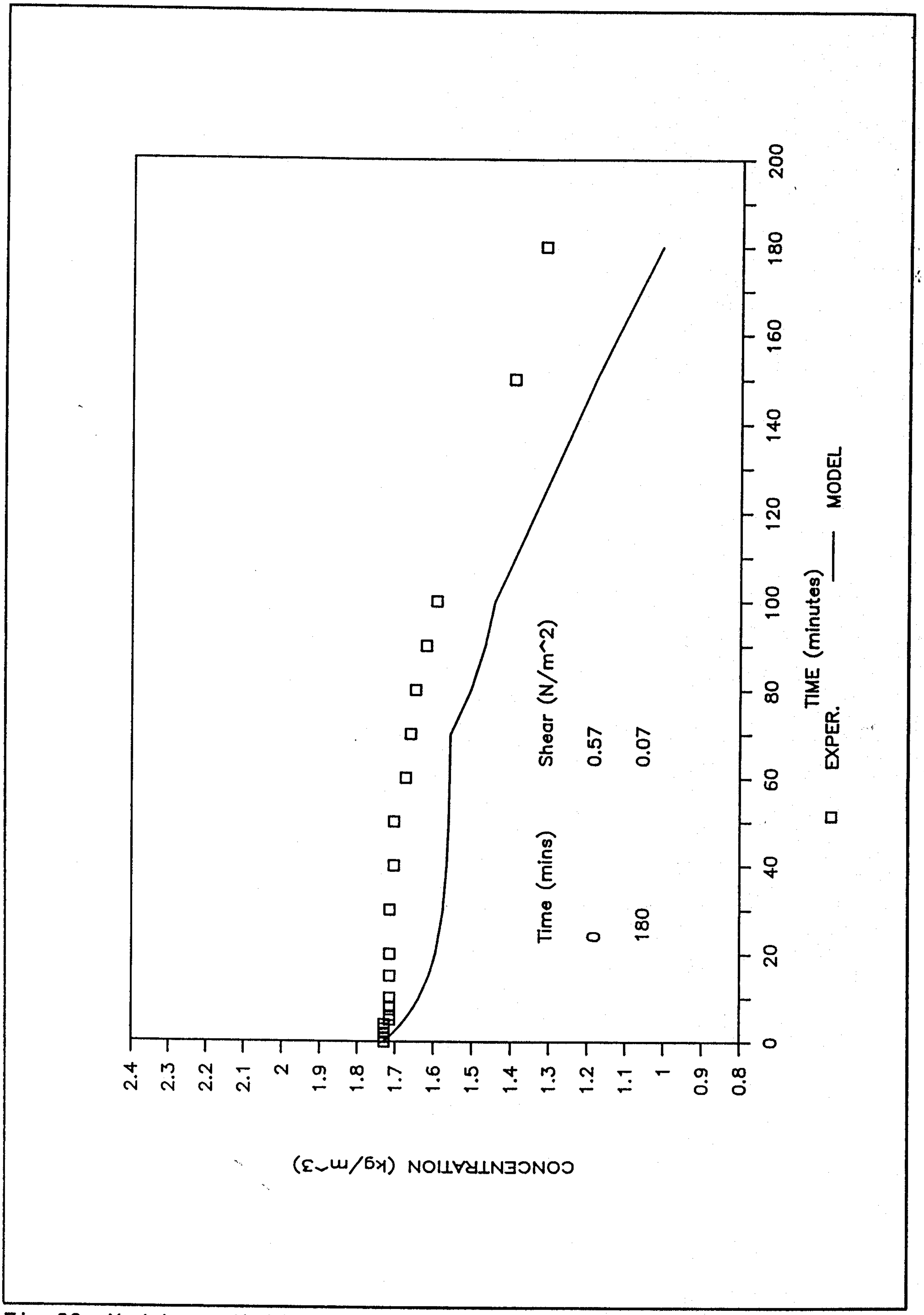

Fig 29 Model prediction Test C6: tor(b)(180mins) = 0.07N/m↑2, C0 = 1.73kg/m↑3

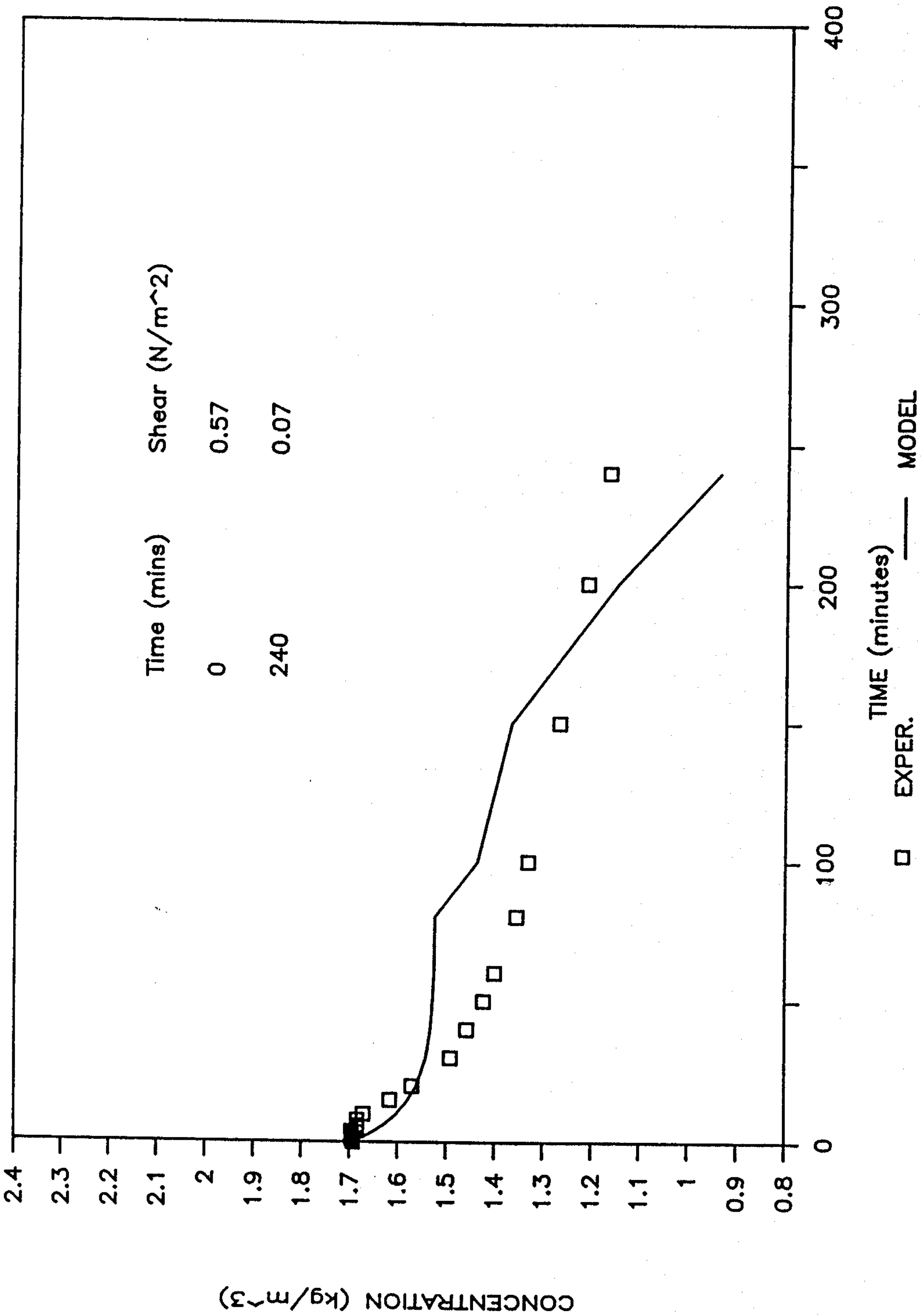

Fig 30 Model prediction Test C7: tor(b)(240mins) = 0.07N/m↑2,
C0 = 1.70kg/m↑3

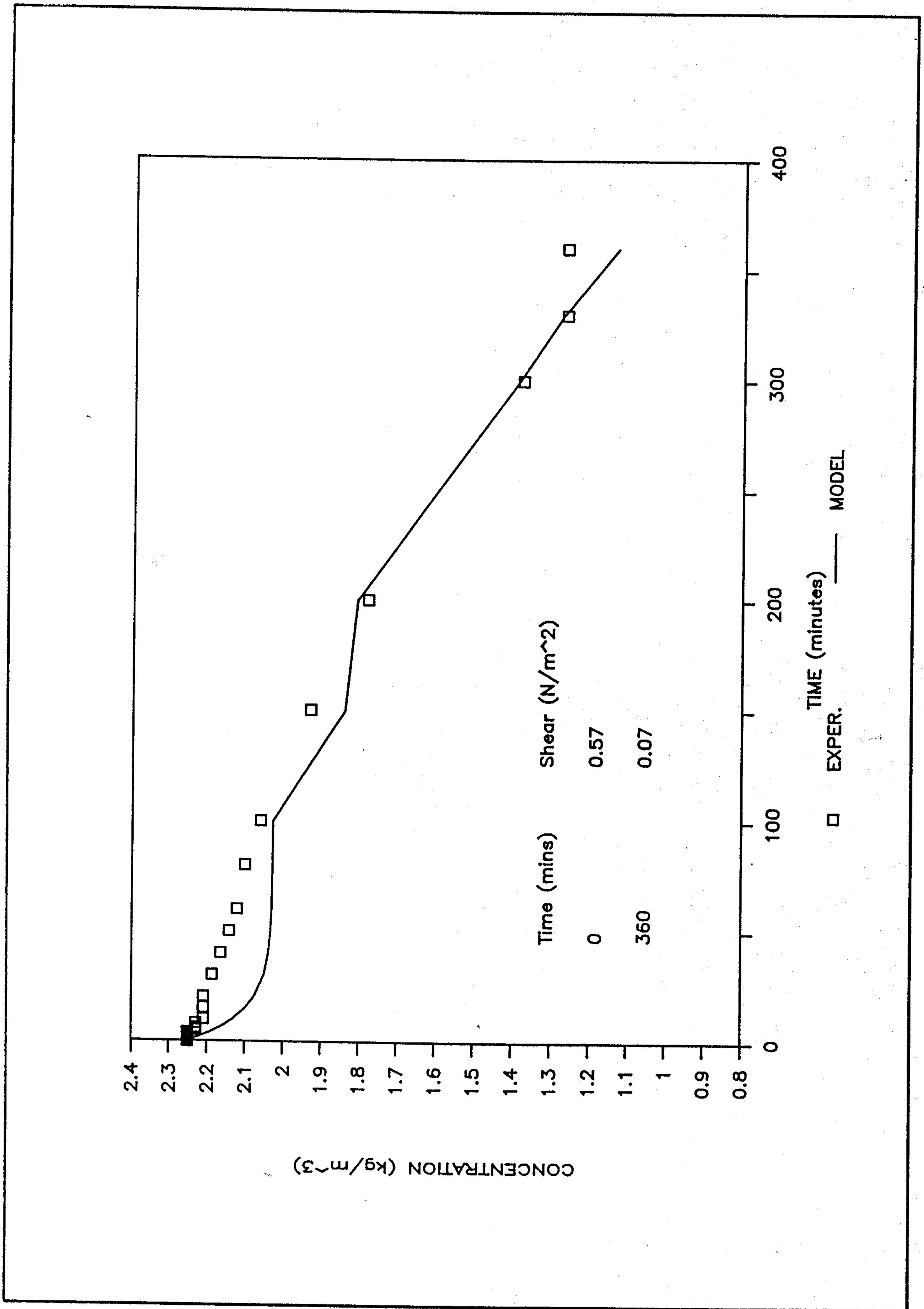

Fig 31 Model prediction Test C8: tor(b)(360mins) = 0.07N/m↑2,
CO = 2.25kg/m↑3

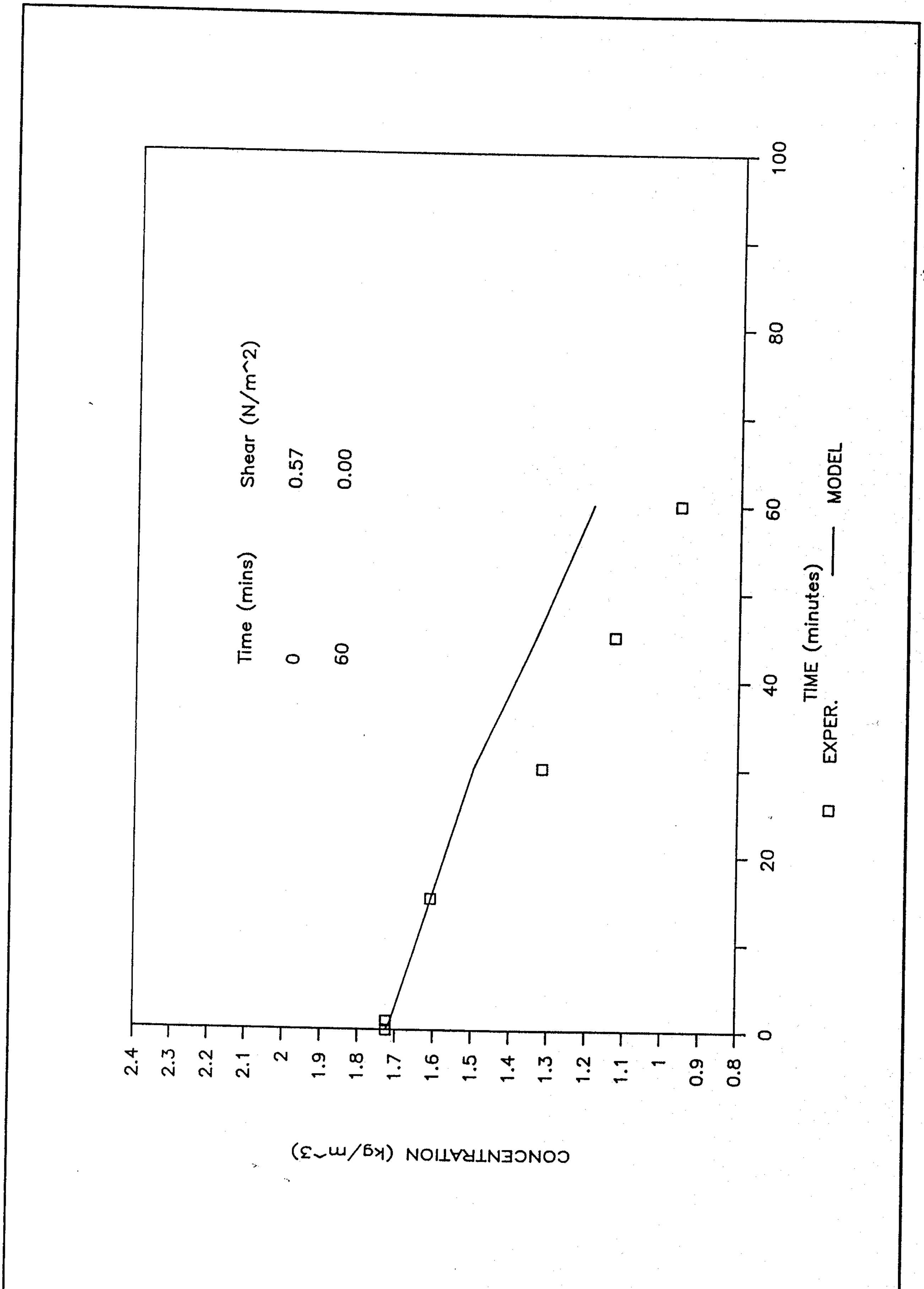

Fig 32 Model prediction Test C9: tor(b)(60mins) = 0.00N/m↑2,
C0 = 1.73kg/m↑3

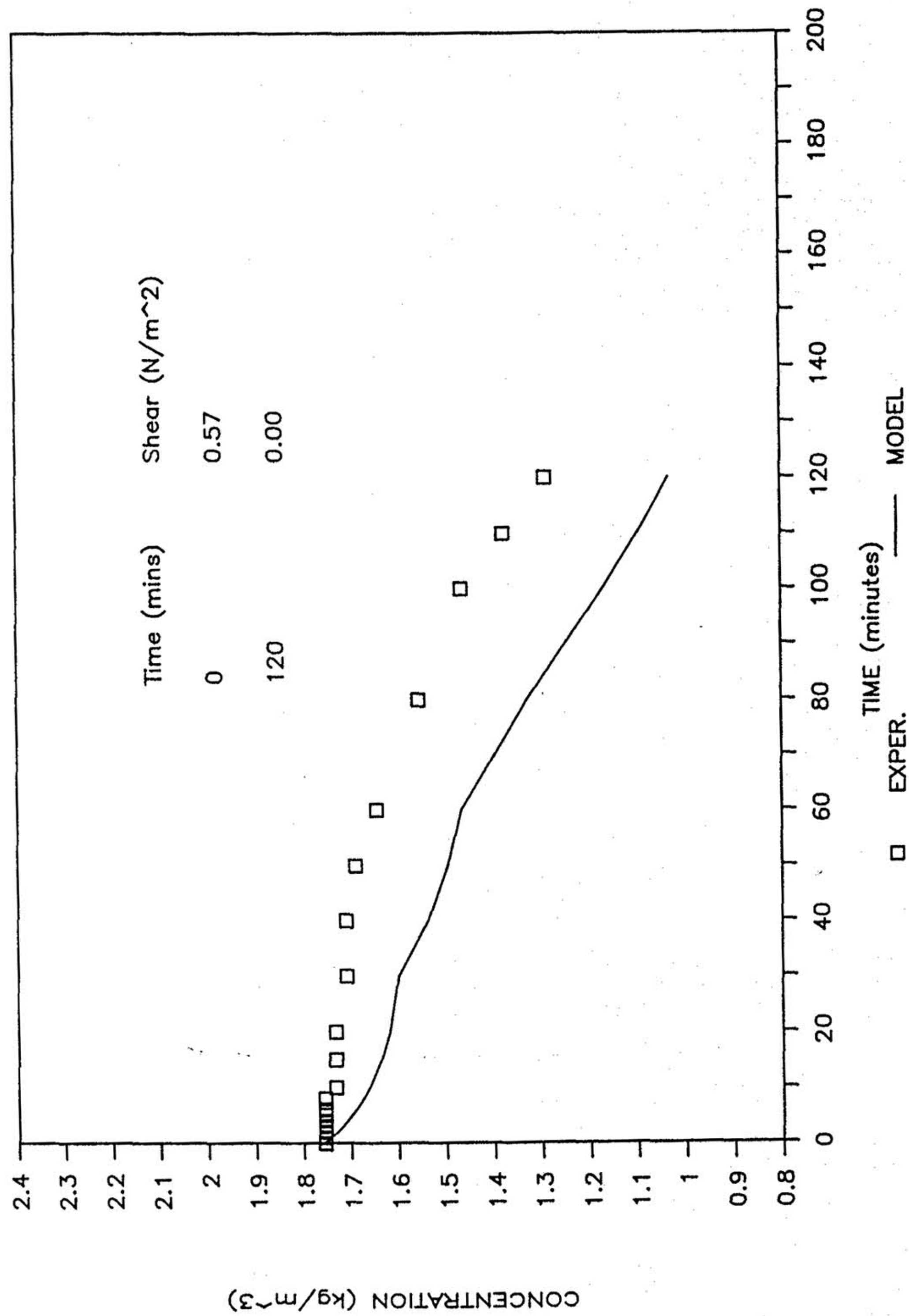

Fig 33 Model prediction Test C10:tor(b)(120mins) = 0.00N/m↑2, C0 = 1.76kg/m↑3

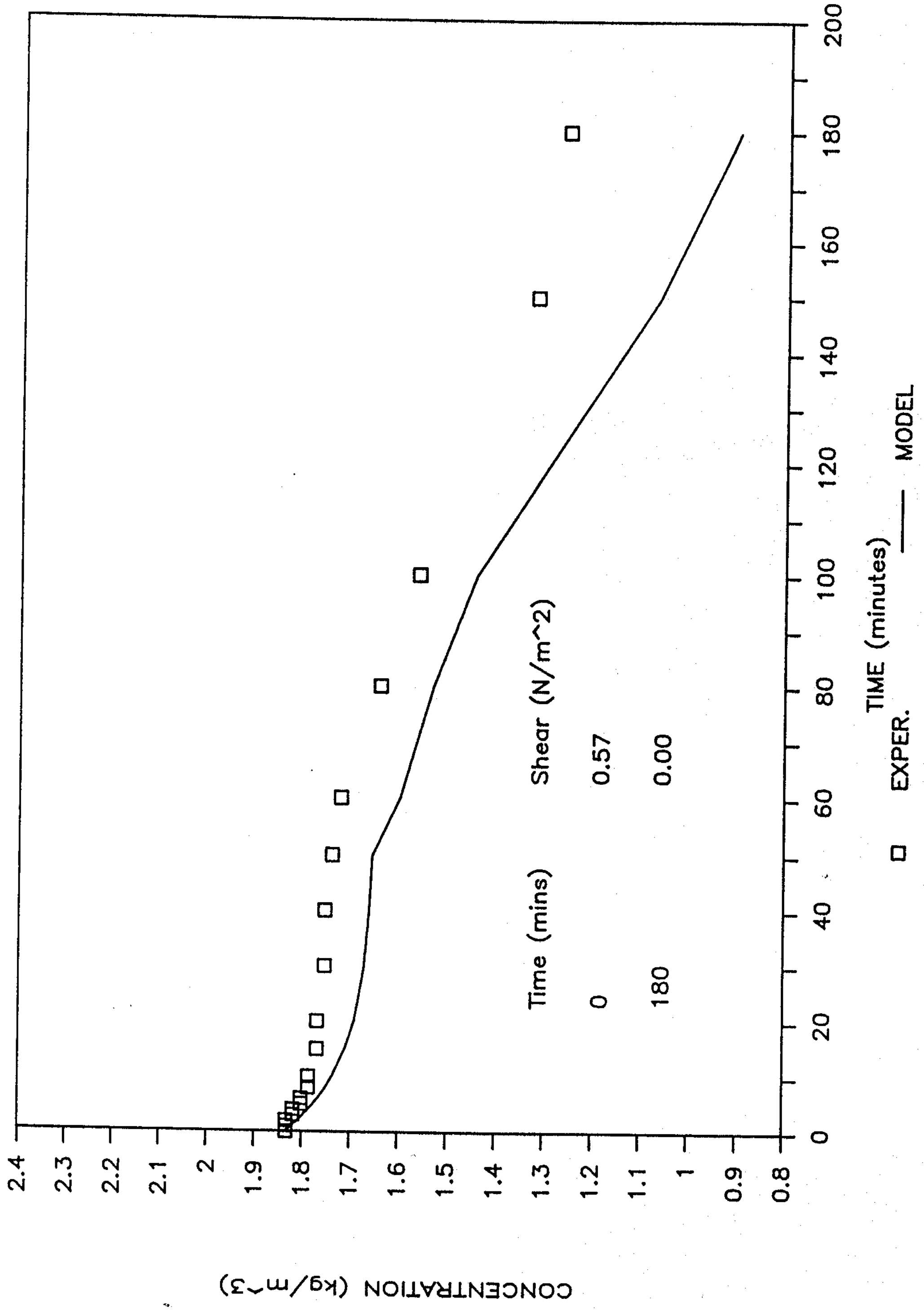

Fig 34 Model prediction Test C11: tor(b)(180mins) = 0.00N/m↑2,
CO = 1.84kg/m↑3

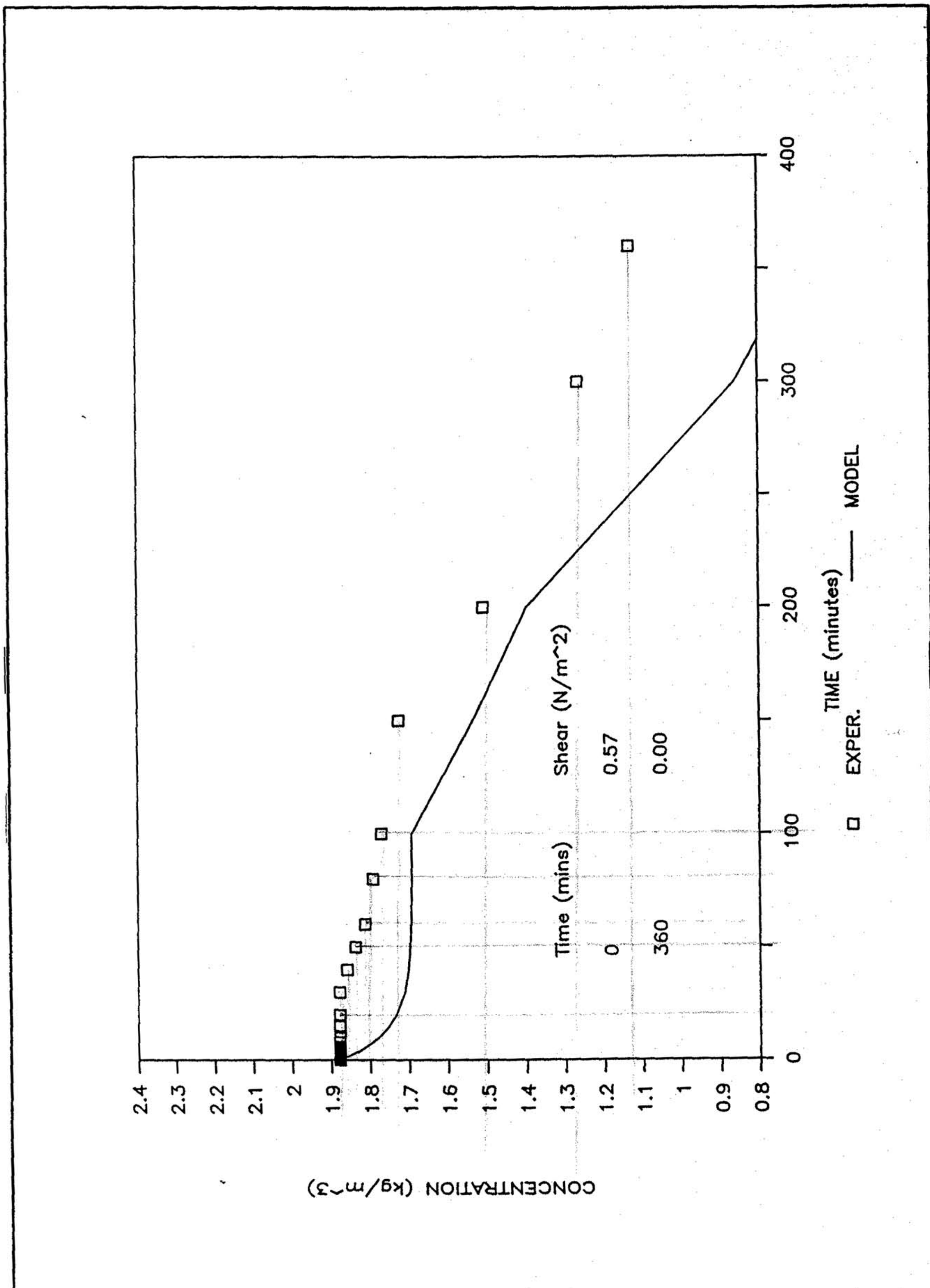

Fig 35 Model prediction Test C12: tor(b)(360mins) = 0.00N/m↑2,

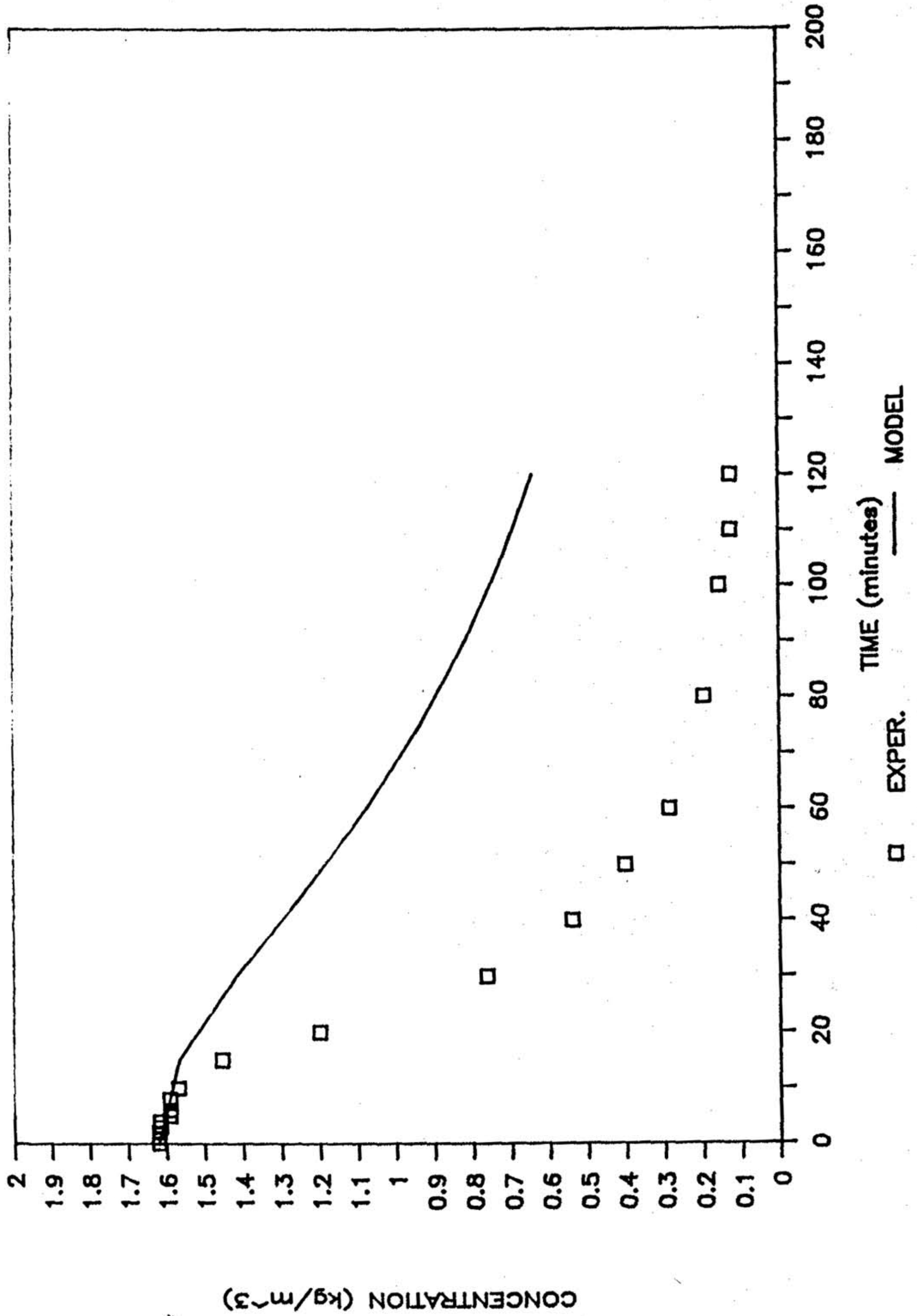

Fig 36 Quiescent settling model predictions Test C4

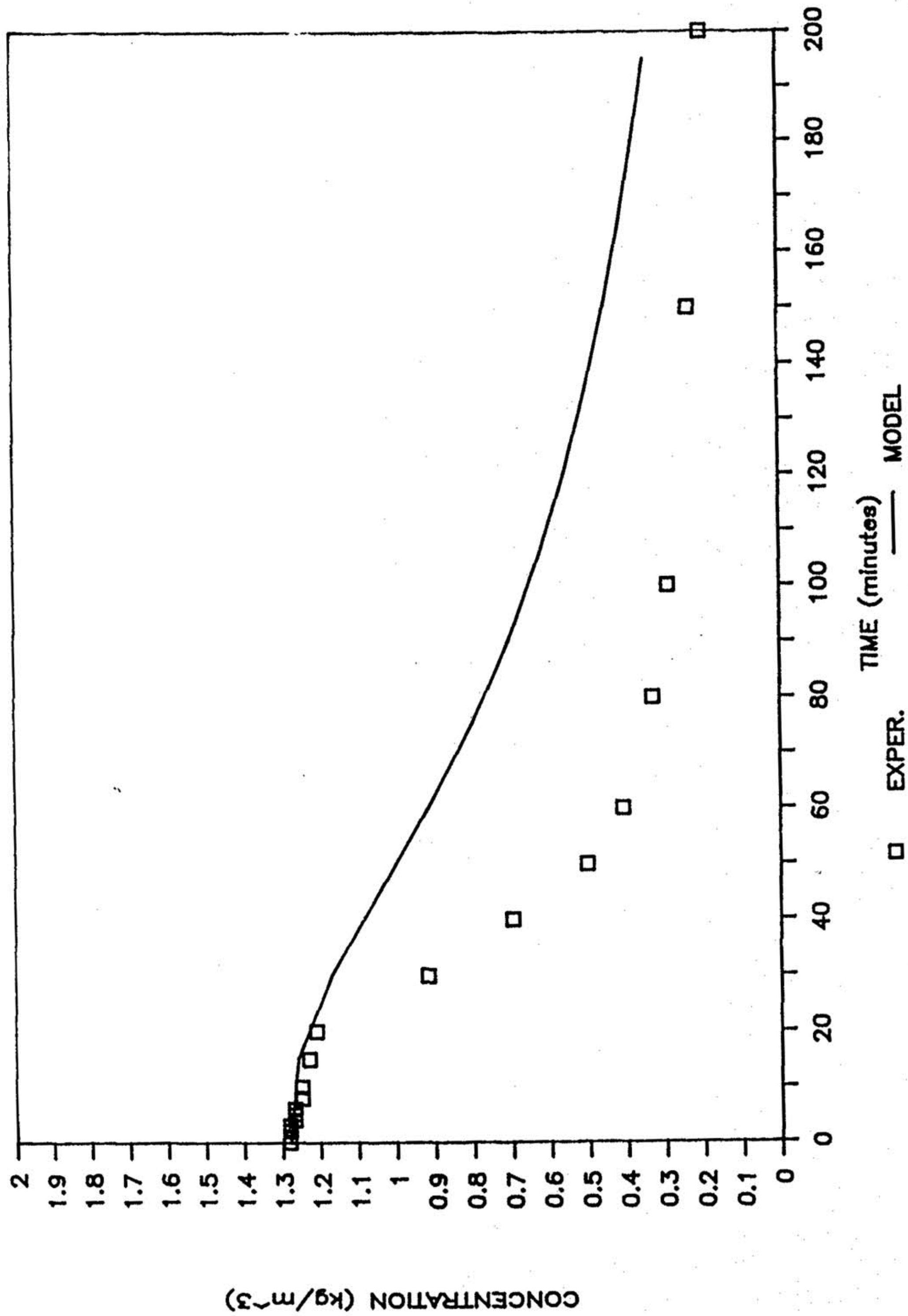

Fig 37 Quiescent settling model predictions Test C5