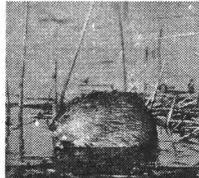


Canada

Alberta

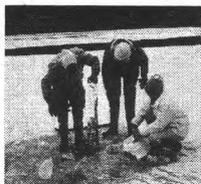
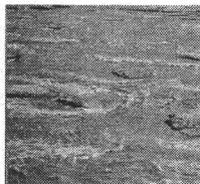


Northern River Basins Study



NORTHERN RIVER BASINS STUDY PROJECT REPORT NO. 85
**CRITICAL SHEAR STRESSES FOR
EROSION AND DEPOSITION OF FINE
SUSPENDED SEDIMENT FROM THE
ATHABASCA RIVER**

GB
1399.9
.C2
K92
1996



8802002
1-11-96

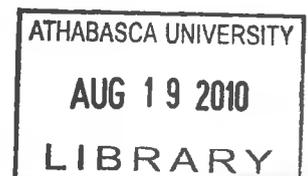
Prepared for the
Northern River Basins Study
under Project 1332-C1

by

B. G. Krishnappan and R. Stephens
National Water Research Institute
Environment Canada

NORTHERN RIVER BASINS STUDY PROJECT REPORT NO. 85
**CRITICAL SHEAR STRESSES FOR
EROSION AND DEPOSITION OF FINE
SUSPENDED SEDIMENT FROM THE
ATHABASCA RIVER**

Published by the
Northern River Basins Study
Edmonton, Alberta
February, 1996



CANADIAN CATALOGUING IN PUBLICATION DATA

Krishnappan, B. G., 1943-

Critical shear stresses for erosion and deposition
of fine suspended sediment from the Athabasca River

(Northern River Basins Study project report,
ISSN 1192-3571 ; no. 85)

Includes bibliographical references.

ISBN 0-662-24633-0

Cat. no. R71-49/3-85E

1. River sediments -- Alberta -- Athabasca River.
 2. Sedimentation transport -- Alberta -- Athabasca River.
 3. Sedimentation and deposition -- Alberta -- Athabasca River.
- I. Stephens, R.
 - II. Northern River Basins Study (Canada)
 - III. Title.
 - IV. Series.

TD387.A42K74 1996 551.3'03'0971232 C96-980210-2

Copyright © 1996 by the Northern River Basins Study.

All rights reserved. Permission is granted to reproduce all or any portion of this publication provided the reproduction includes a proper acknowledgement of the Study and a proper credit to the authors. The reproduction must be presented within its proper context and must not be used for profit. The views expressed in this publication are solely those of the authors.

PREFACE:

The Northern River Basins Study was initiated through the "Canada-Alberta-Northwest Territories Agreement Respecting the Peace-Athabasca-Slave River Basin Study, Phase II - Technical Studies" which was signed September 27, 1991. The purpose of the Study is to understand and characterize the cumulative effects of development on the water and aquatic environment of the Study Area by coordinating with existing programs and undertaking appropriate new technical studies.

This publication reports the method and findings of particular work conducted as part of the Northern River Basins Study. As such, the work was governed by a specific terms of reference and is expected to contribute information about the Study Area within the context of the overall study as described by the Study Final Report. This report has been reviewed by the Study Science Advisory Committee in regards to scientific content and has been approved by the Study Board of Directors for public release.

It is explicit in the objectives of the Study to report the results of technical work regularly to the public. This objective is served by distributing project reports to an extensive network of libraries, agencies, organizations and interested individuals and by granting universal permission to reproduce the material.

**NORTHERN RIVER BASINS STUDY
PROJECT REPORT RELEASE FORM**

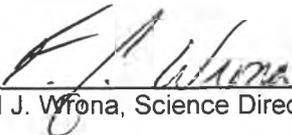
This publication may be cited as:

B. G. Krishnappan and R. Stephens. 1996. *Northern River Basins Study Project Report No. 85, Critical Shear Stresses for Erosion and Deposition of Fine Suspended Sediment From the Athabasca River*, Northern River Basins Study, Edmonton, Alberta.

Whereas the above publication is the result of a project conducted under the Northern River Basins Study and the terms of reference for that project are deemed to be fulfilled,

IT IS THEREFORE REQUESTED BY THE STUDY OFFICE THAT;

this publication be subjected to proper and responsible review and be considered for release to the public.



(Dr. Fred J. Wrona, Science Director)

14 Feb 96

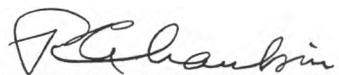
(Date)

Whereas it is an explicit term of reference of the Science Advisory Committee "to review, for scientific content, material for publication by the Board",

IT IS HERE ADVISED BY THE SCIENCE ADVISORY COMMITTEE THAT;

this publication has been reviewed for scientific content and that the scientific practices represented in the report are acceptable given the specific purposes of the project and subject to the field conditions encountered.

SUPPLEMENTAL COMMENTARY HAS BEEN ADDED TO THIS PUBLICATION: [] Yes [] No



(Dr. P. A. Larkin, Ph.D., Chair)

Feb 14/1996

(Date)

Whereas the Study Board is satisfied that this publication has been reviewed for scientific content and for immediate health implications,

IT IS HERE APPROVED BY THE BOARD OF DIRECTORS THAT;

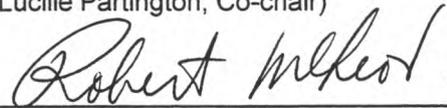
this publication be released to the public, and that this publication be designated for: [] **STANDARD AVAILABILITY** [] **EXPANDED AVAILABILITY**



(Lucille Partington, Co-chair)

14/02/96

(Date)



(Robert McLeod, Co-chair)

14/02/96

(Date)

CRITICAL SHEAR STRESSES FOR EROSION AND DEPOSITION OF FINE SUSPENDED SEDIMENT FROM THE ATHABASCA RIVER

STUDY PERSPECTIVE

Suspended sediments are known to absorb and transport contaminants and are one vector by which contaminants and nutrients can travel on in the river. In order to accurately comprehend and model the aquatic ecosystem, an understanding of how the sediment interacts with the river system is required. Understanding the transport characteristics of fine sediments is essential for modelling the transport, bioaccumulation and fate of contaminants in the river systems. A previous Northern River Basins Study report "Size Distribution and Transport of Suspended Particles" (NRBS Report Number 51) demonstrated that pulp mill effluent affects the physical transport characteristics of the river sediment by causing suspended sediment to form into flocs and settle out.

To accurately model suspended sediment transport, flocculation of the suspended sediment due to pulp mill effluents must be taken into account. In this study, sediments from the Athabasca River near Hinton were tested in a laboratory flume and their transport parameters measured, with and without the presence of pulp mill effluent. The study provides quantitative information on critical conditions for erosion and deposition of sediment flocs that are essential for modelling the contaminant transport. The influence of the pulp mill effluent on the transport behaviour was also quantified.

The results of this study have led to the development of a new algorithm for the transport of fine sediment in the Athabasca River. This algorithm was incorporated into the Athabasca River contaminant fate model and the results are described in "Implementation of a New Algorithm for Simulation of Fine Grained Sediment Transport in the Athabasca River" (NRBS Report Number 136).

Related Study Questions

5. *Are the substances added to the rivers by natural and man made discharges likely to cause deterioration of the water quality?*
13. *a) What predictive tools are required to determine the cumulative effects of man-made discharges on the water and aquatic environment?*

b) What are the cumulative effects of man-made discharges on the water and aquatic environment?
14. *What long term monitoring programs and predictive models are required to provide an ongoing assessment of the state of the aquatic ecosystems. These programs must ensure that all stakeholders have the opportunity for input.*

REPORT SUMMARY

The transport characteristics of the fine sediment are essential parameters for modelling the transport, fate and bioaccumulation of contaminants in river systems. In this study, which was carried out for the Northern River Basins Study (NRBS), sediments from the Athabasca River near Hinton, Alberta were tested in the rotating flume of the National Water Research Institute in Burlington, Ontario and their transport parameters measured. A brief description of the experimental procedure and some significant results are presented in this report.

Sediment and water samples from the Athabasca River near Hinton were brought to the rotating flume and were tested for erosion and deposition characteristics. In the deposition tests, a sediment-water mixture was thoroughly mixed in the flume and then subjected to different bed shear stresses. During the deposition process, concentration and size distribution of sediment in suspension were measured as a function of time. From these measurements, it was possible to quantify the critical condition for complete deposition of the sediment and the steady state concentration of sediment that would stay in suspension for ever for a particular bed shear stress. Size distribution data showed that the particles flocculated as they were deposited and the equilibrium size distribution of the sediment flocs was a function of bed shear stress. The effect of the pulp mill effluent on the deposition process was also tested by adding a known quantity of the effluent brought from the pulp mill to the flume and repeating the experiment. The results showed that the pulp mill effluent enhanced the flocculation mechanism and increased the sediment deposition rate.

The erosion characteristics were studied by allowing the sediment to deposit completely on the flume bed and then applying bed shear stresses in steps. As in deposition tests, concentration and size distribution of the eroded sediment were measured at different shear stresses. From these measurements, it was possible to determine the critical shear stress for erosion and the erosion rate function for different shear stress steps.

The quantitative knowledge gained in this study has lead to the development of a new algorithm for fine sediment transport that can be incorporated in contaminant transport models such as WASP and make realistic predictions of contaminant impact on the ecosystem of the Athabasca River.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the technical assistance of Mr. Barry Moore of Technical Operations Section at NWRI in the collection of large volume samples from the Athabasca River. The funding for this study was provided by the Northern River Basins Study (NRBS). Dr. Terry Prowse, the Component Leader of the Hydrology/Hydraulics and Sediment Transport subgroup of NRBS recommended this study to the Scientific Review Committee and Mr. Jim Choles of Alberta Environmental Protection acted as the Scientific Authority. We thank both of them for their support. The review comments of Dr. Marsalek, the Project Chief of the Contaminant Pathways and Control Project in the Aquatic Ecosystem Protection Branch at NWRI, are greatly appreciated. The comments from the anonymous reviewers were very valuable for improving the quality of the report.

TABLE OF CONTENTS

| | |
|--|------------|
| <u>REPORT SUMMARY</u> | i |
| <u>ACKNOWLEDGEMENTS</u> | ii |
| <u>TABLE OF CONTENTS</u> | iii |
| <u>LIST OF TABLES</u> | iv |
| <u>LIST OF FIGURES</u> | v |
| | |
| 1.0 <u>INTRODUCTION</u> | 1 |
| | |
| 2.0 <u>EXPERIMENTAL EQUIPMENT AND PROCEDURE</u> | 1 |
| 2.1 THE FLUME | 1 |
| 2.2 INSTRUMENTATION | 1 |
| 2.3 MEASUREMENT OF SHEAR STRESS | 4 |
| 2.4 COLLECTION AND PREPARATION OF SEDIMENT SAMPLE | 5 |
| 2.5 DEPOSITION AND EROSION TESTS | 5 |
| | |
| 3.0 <u>RESULTS AND DISCUSSION</u> | 7 |
| 3.1 DEPOSITION TESTS | 9 |
| 3.2 EROSION TESTS | 15 |
| 3.3 APPLICATION TO THE ATHABSCA RIVER | 20 |
| | |
| 4.0 <u>SUMMARY AND CONCLUSIONS</u> | 20 |
| | |
| 5.0 <u>REFERENCES</u> | 21 |
| | |
| <u>APPENDIX A</u> <u>TERMS OF REFERENCE</u> | 22 |

LIST OF TABLES

Table 1: Summary of experimental conditions 7
Table 2: Summary of results from deposition experiments 14

LIST OF FIGURES

| | | |
|-------------------|---|-----------|
| Figure 1: | Sectional view of NWRI's rotating flume | 2 |
| Figure 2a: | Top view of the rotating flume | 3 |
| Figure 2b: | Schematic view of the Malvern Particle Size Analyzer arrangement beneath the flume | 6 |
| Figure 3: | Average bed-shear velocity as a function of relative tangential velocity | 8 |
| Figure 4: | Time variatio of concentration of suspended sediment during depostion under different bed-shear stresses | 10 |
| Figure 5: | Time variation of suspended sediment concentration during depostion under different initial concentrations | 11 |
| Figure 6: | Size distribution of suspended sediment flocs during deposition (Test no. 5; bed-shear stress = 0.324 N/m²) | 12 |
| Figure 7: | Size distirubiton of suspended sediment flocs during deposition (Test no. 1; bed-shear stress = 0.121 N/m²) | 13 |
| Figure 8: | Sediment concentration vs. Time during deposition at a constant shear stres with and without pulp mill effluent | 16 |
| Figure 9: | Size distribution of sediment flocs with and without pup mill effluent | 17 |
| Figure 10: | Erosion characteristics of the deposited sediment for Test no. 11 | 18 |
| Figure 11: | Size distribution of eroded sediment in Test no. 11 | 19 |

1.0 INTRODUCTION

This project was undertaken for the Northern River Basins Study (NRBS) to measure transport parameters such as the critical shear stresses for erosion and deposition for sediments from the Athabasca River. These parameters are needed to model the sediment and the associated contaminant transport through the river system. An earlier study carried out in the Athabasca River near Hinton by Krishnappan et al. (1994) had shown that the suspended sediments in the river were transported in a flocculated form. The pulp mill effluent from the Weldwood Pulp Mill at Hinton had an influence on the Flocculation mechanism and increased the deposition rate of sediment in the reach downstream of the out fall. In this study, we have made an attempt to investigate, under controlled conditions the deposition process of the Athabasca River sediment, the influence of the pulp mill effluent on the deposition process, and the shear stresses that are needed to re-suspend the deposited sediment. This involved testing the sediment-water mixture from the Athabasca River in our Rotating Circular flume at the National Water Research Institute in Burlington, Ontario. Details of the experimental investigation are outlined in this report.

2.0 EXPERIMENTAL EQUIPMENT AND PROCEDURE

2.1 THE FLUME

The rotating flume used for this study is 5.0 m in mean diameter, 0.30 m in width, 0.30 m in depth and rests on a rotating platform. A counter-rotating top cover, called the ring, fits inside the flume and makes contact with the surface of the sediment-water mixture in the flume. By rotating the platform and the ring assembly in opposite directions, it is possible to generate nearly two-dimensional shear flows and to study the behaviour of the sediment under different flow conditions. The flume and the ring can each be rotated up to a maximum rate of three revolutions per minute. A sectional view of the flume is shown in Fig. 1 and a photograph showing the top view of the flume with instruments is shown in Fig. 2a.

2.2 INSTRUMENTATION

The flume is equipped with a Laser Doppler Anemometer (LDA) to measure the flow field, a Preston tube to measure the bed shear stress, a Malvern Particle Size Analyzer (MPSA) to measure the in-situ particle size distribution in the flow and an optical turbidity sensor (OSLIM) to measure the suspended sediment concentration. The instruments activated for the present experiments were the Preston tube, the MPSA and the OSLIM sensor.

The Preston tube is similar to the Pitot tube and it is mounted in such a way that it lays flat on the flume bed facing the flow. The tube entered the flume through a water-tight sleeve attached to the outside flume wall. The difference between the dynamic and static pressure was measured with a Valedyne model DP-45 pressure transducer with a diaphragm having a pressure capacity equivalent to 25.4 millimetre of water. The calibration proposed by Patel (1965) was adopted to compute the bed shear stress from the pressure difference measured with the pressure transducer.

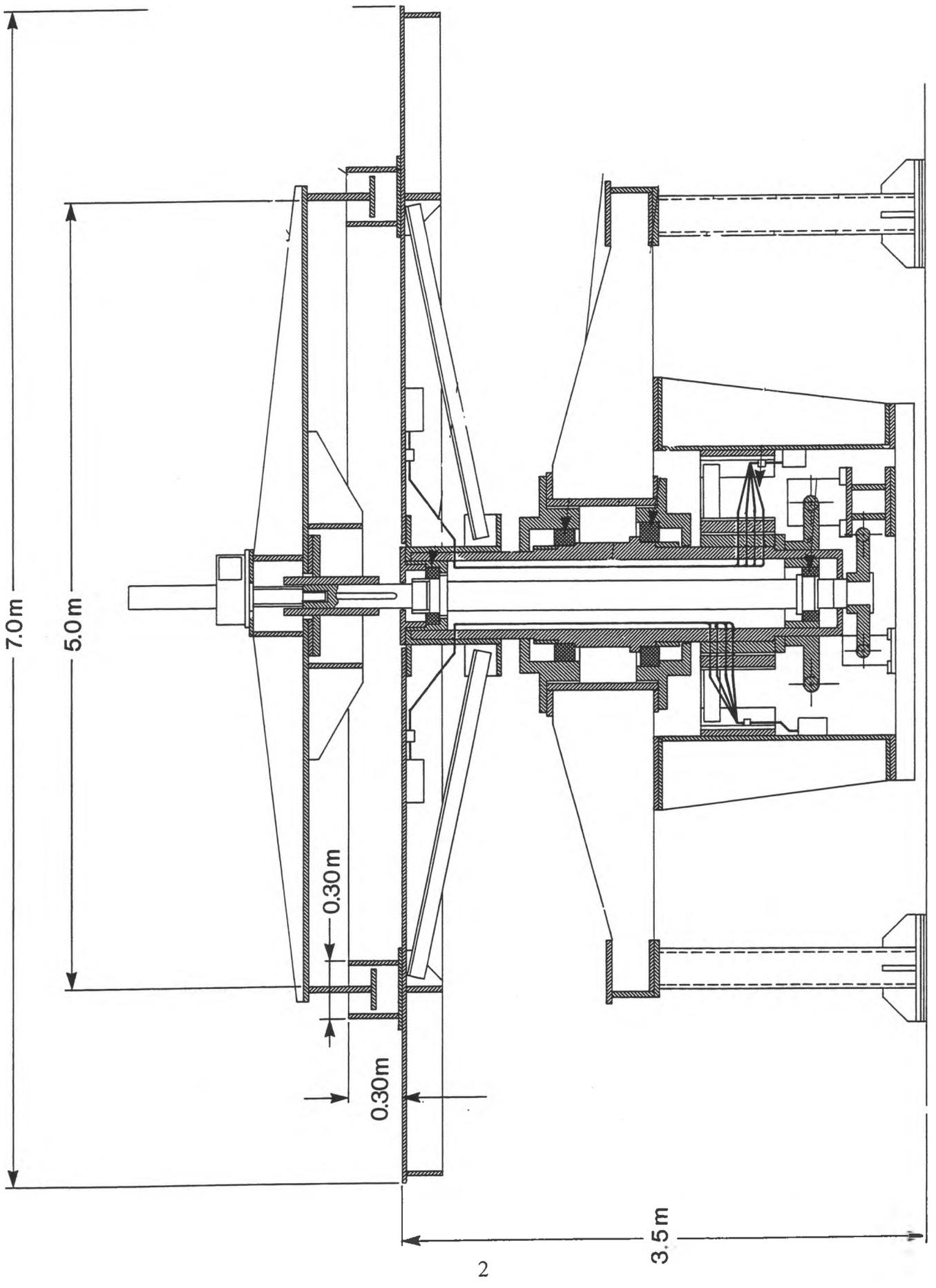


Fig. 1 Sectional view of NWRI's Rotating Flume



Fig. 2a Top view of the Rotating Flume

The MPSA operates on the light diffraction principle (Fraunhofer diffraction). Complete details of the method can be found in Weiner (1984). Continuous in-situ measurements of floc sizes were made by mounting the MPSA on the rotating platform below the flume so that the flow through sensor was located directly below the centre-line of the flume cross-section (See Fig. 2b). The sediment suspension was drawn continuously from the flume by gravity through a 5 mm tube. The suspension passed through the sensor and entered into a reservoir from where it was pumped back into the flume. The sampling end of the tube was bent at a right angle, similar to a Pitot tube, so that the intake would face directly into the flow. The length of the tube was kept to a minimum to avoid floc disruption and the withdrawal rate was just large enough to avoid deposition of sediment in the tubes.

The measuring principle of the OSLIM sensor is based on the attenuation of a light beam, caused by absorption and reflection by the sediment particles. The light source used in this instrument is an infra-red light emitting diode (LED). The light absorption is dependent on the particle size distribution but by pumping the suspension through a short, small diameter tube just upstream of the sensor and allowing the shear in the tube to break up the flocs, the error caused by varying size distribution was kept to a minimum. The sediment suspension was pumped continuously from the flume through a 5 mm tube that entered the flume through the outside wall. The sampling position was at the centre of the flume and at mid depth. The suspension that passed through the sensor was pumped back into the flume making sure that the discharge location was downstream of the intake location. The pumping rate was such that no deposition of the sediment occurred within the tube.

2.3 MEASUREMENT OF SHEAR STRESS

The characteristics of the flows generated using the flume were studied in detail by Krishnappan (1993) and Petersen and Krishnappan (1994). These studies established that the flow fields generated by rotating the flume and the ring simultaneously are nearly two dimensional and the two dimensionality of the flow field improved when the ring rotated slightly faster than the flume. For a flow depth of 12.0 cm, the ring speed had to be 17% faster than the flume speed. For the present experiments, a flow depth of 12.0 cm was used and the bed shear stresses were measured using the Preston tube. Details of the shear stress experiments are described in Krishnappan et al (1994). The measurement of bed shear stress using the Preston tube has to be restricted to clear water flows because the presence of particles was known to affect the performance of the Preston tube. A calibration relationship between the bed shear stress and the relative tangential speed of the ring with respect to the flume bottom for clear water, shown in Fig. 3, was adopted for the present study under the assumption that the presence of sediment in low concentrations does not affect the bed shear stress values.

2.4 COLLECTION AND PREPARATION OF SEDIMENT SAMPLE

River water and sediment samples were collected from the Athabasca River upstream of the Pulp mill out fall at Hinton. A pumping system, similar to that used in cleaning swimming pools, was used to vacuum the sediment deposited on the gravel bed and pump river water into 100 l plastic containers which could be sealed tightly for shipping. Eight such containers were filled. Care was taken to obtain representative samples of the entire cross-section. In addition, about 50 l of effluent was collected from the discharge well of the pulp mill out fall and put in suitable containers for shipping.

2.5 DEPOSITION AND EROSION TESTS

Before beginning a deposition test, the sediment-water suspension was thoroughly mixed in the flume with a mechanical mixer to break up existing flocs. The ring was then lowered to the desired position so that the water depth below the ring was 12.0 cm. The ring penetrated the water surface by about 3 mm to ensure proper contact between the ring and the water surface. The MPSA and OSLIM sensors were then checked to ensure that they were operating properly. Having completed all preparations, the flume and the ring were set in motion and the speeds of the flume and the ring were increased to 2 rpm and 2.5 rpm respectively to obtain a suspended sediment concentration in excess of that sustainable by the flow at chosen test speeds. After twenty minutes, the flume and the ring were slowed down to their respective test speeds in accordance with the established speed ratio for the given water depth. Samples were withdrawn from the flume at intervals of 5 minutes during the first hour of the test and every ten minutes thereafter until completion of the test. Each time a sample was drawn, the volume removed was replaced by clear river water. A test was considered to be complete after the suspended sediment concentration remained nearly constant for one hour. The samples were taken at mid-depth as tests had shown that the concentration was nearly uniform over the depth. The concentration of each sample was determined by filtration, drying and weighing. Along with the manual sampling, sediment concentration was also determined with the OSLIM sensor. The size distribution of the suspension was measured at regular intervals with the MPSA and recorded on a computer disc for later analysis. This way, the formation of flocs and changes in the size distribution of flocs with time could be monitored. Once a test was completed, the procedure was repeated for other flume speeds.

Before beginning an erosion test, the sediment-water mixture in the flume was left undisturbed for a period of time to allow the sediment to settle and consolidate on the flume bed. Three different consolidation times ranging from 42 hours to 110 hours were tested. For each erosion test, care was taken to ensure that the water depth was 12 cm, that the ring penetrated the water surface sufficiently and that the MPSA and the OSLIM were functioning properly. Having completed all preparations, the flume and the ring were set in motion beginning with the lowest flume speed. As before, samples were withdrawn from the flume and the change in concentration was monitored with the OSLIM at intervals of 5 to 10 minutes until the sediment concentration reached a steady state value for each flume speed setting. When this stage was reached, the flume and the ring speeds were increased to the next step. This sequence was repeated until the maximum permissible ring speed was reached. The size distributions of the suspended sediment were again measured at regular intervals with the MPSA and recorded on a computer disc for later analysis.

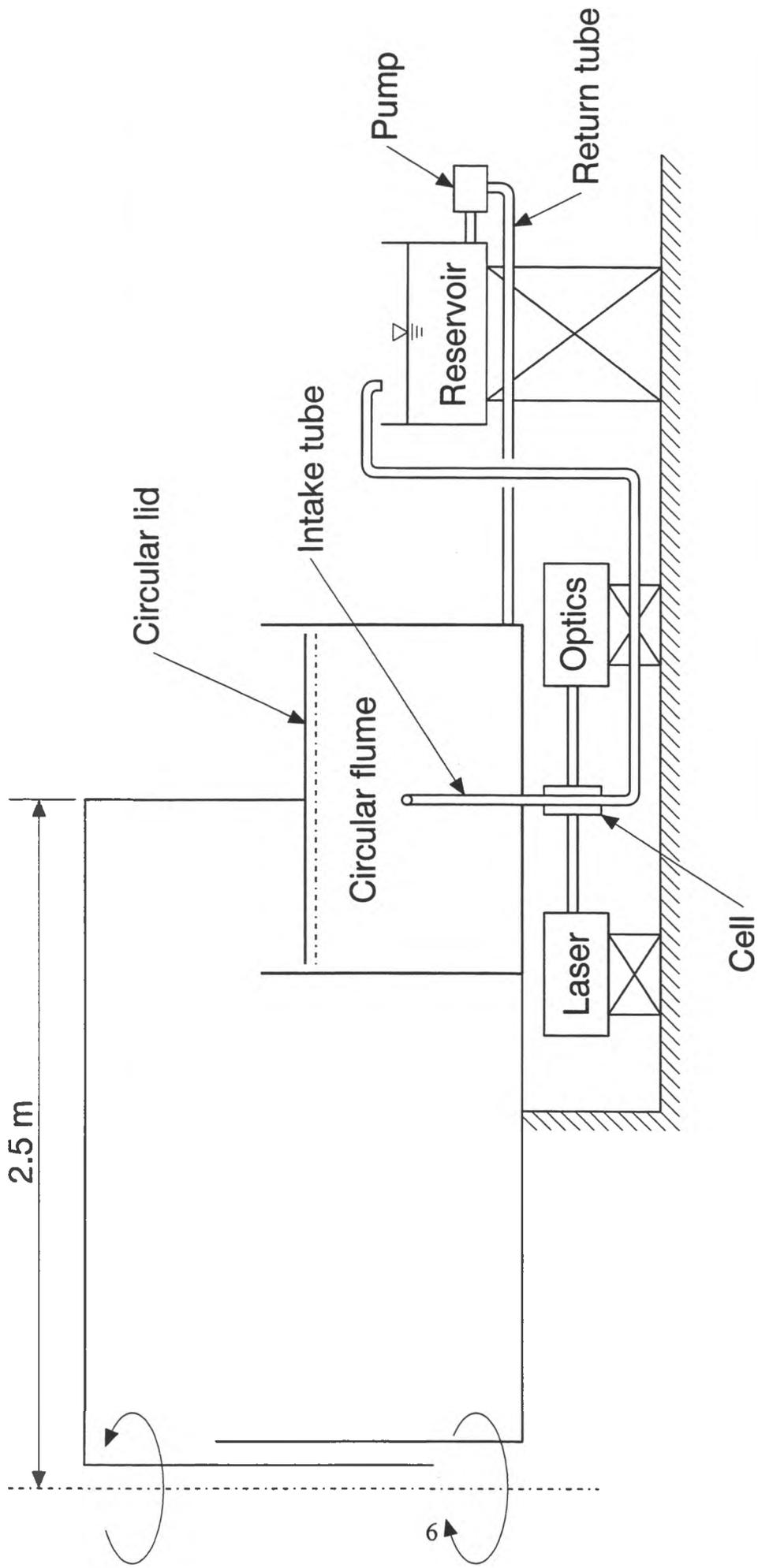


Fig. 2b Schematic view of the Malvern Particle Size Analyzer arrangement beneath the flume

3.0 RESULTS AND DISCUSSION

Altogether, twelve tests were carried out for the Athabasca River sediment. A summary of the experimental conditions is given in the table below:

Table 1. Summary of experimental conditions

| Test No. | Experiment Type | Shear stress N/m ² | Initial Conc. Mg/l | Age of deposit in hr | Effluent conc. In % by vol. |
|----------|-----------------|-------------------------------|--------------------|----------------------|-----------------------------|
| 1 | Deposition | 0.121 | 200 | n/a | 0 |
| 2 | Deposition | 0.169 | 200 | n/a | 0 |
| 3 | Deposition | 0.213 | 200 | n/a | 0 |
| 4 | Deposition | 0.259 | 200 | n/a | 0 |
| 5 | Deposition | 0.324 | 200 | n/a | 0 |
| 6 | Deposition | 0.259 | 250 | n/a | 0 |
| 7 | Deposition | 0.324 | 250 | n/a | 0 |
| 8 | Deposition | 0.259 | 250 | n/a | 4 |
| 9 | Deposition | 0.259 | 250 | n/a | 4 |
| 10 | Erosion | n/a | n/a | 65 | 4 |
| 11 | Erosion | n/a | n/a | 110 | 4 |
| 12 | Erosion | n/a | n/a | 42 | 4 |

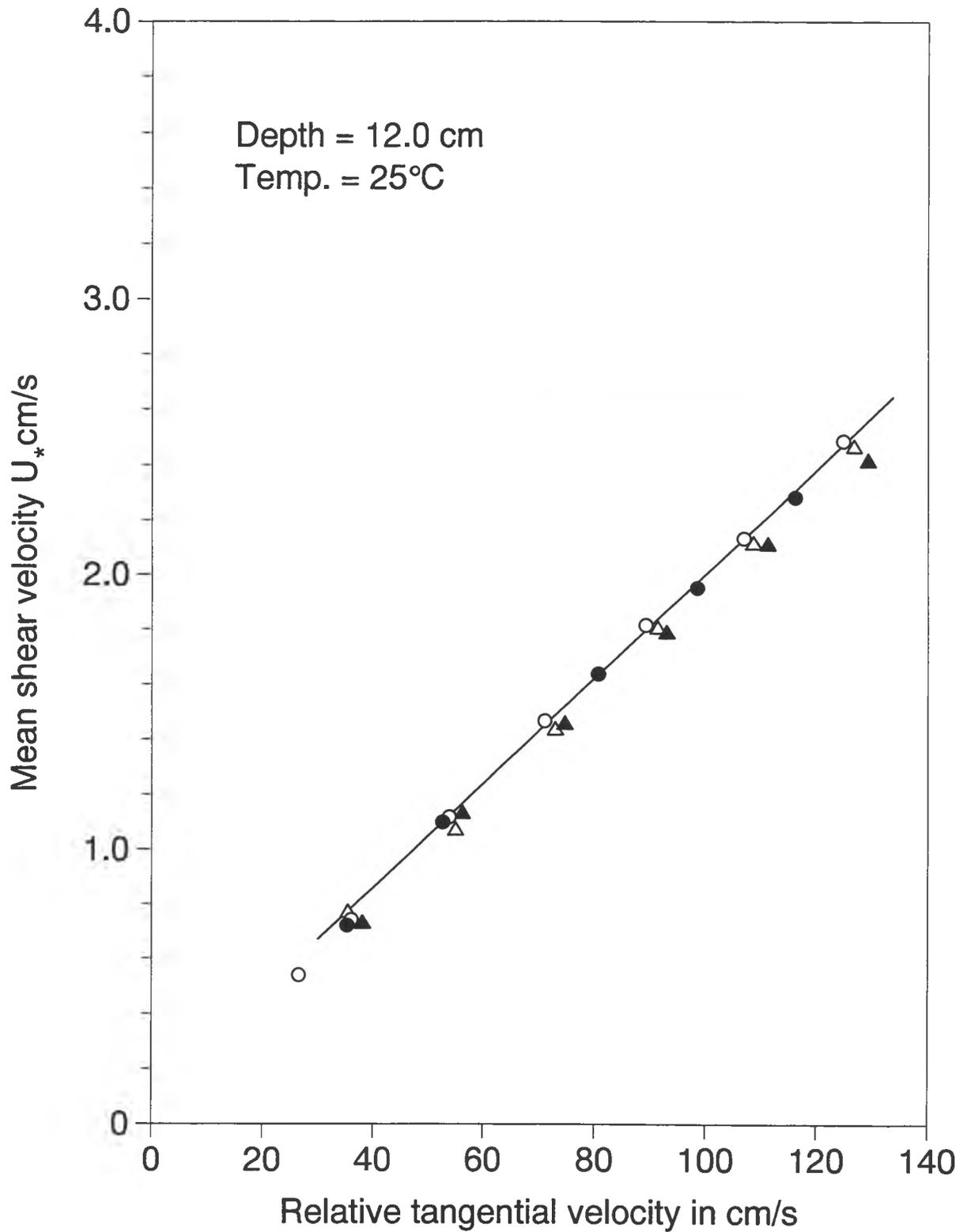


Fig. 3 Average bed-shear velocity as a function of relative tangential velocity

3.1 DEPOSITION TESTS

Deposition experiments were carried out for five different bed shear stresses (Test Nos. 1 to 5). Effects of both the initial concentration (Test Nos. 6 and 7) and the pulp mill effluent (Test Nos. 8 and 9) were also tested during the deposition tests. Fig 4 shows the time variation of concentration of sediment in suspension for deposition tests in which the initial concentration was held constant and the bed shear stress was varied. In this figure, four out of the five shear stress tests are shown. Results of Test No. 2 were not plotted in this figure to avoid clutter. It can be seen from this figure that the concentration decreases initially and gradually reaches a steady state value. The time to reach steady state value and the magnitude of steady state concentration depend on the bed shear stress. The time to reach steady state decreases as the shear stress increases whereas the magnitude of the steady state concentration increases with the shear stress. It is evident from this figure that deposition of sediment occurred under all shear stresses tested. The deposition increases as the shear stress is lowered, and at the lowest shear stress tested, the concentration of the sediment in suspension drops to about 30 mg/l from the initial concentration of 200 mg/l. If the shear stress were reduced further, all of the sediment would have deposited. The shear stress that would correspond to such a condition is defined as the critical shear stress for deposition. For the Athabasca River sediment this value is slightly lower than 0.121 N/m², the lowest shear stress tested in the present experiments.

The effect of the initial concentration on the deposition process is shown in Figure 5. In this figure, the results of Test No. 5 is compared with that of Test No. 7 as an example. These two tests have the same bed shear stress (0.324 N/m²) but different initial concentrations (200 mg/l in Test No. 5 and 250 mg/l in Test No. 7). From this figure, it can be seen that the steady state concentration is different for the two test. The test with the higher initial concentration produces a higher steady state concentration and hence one can conclude that the steady state concentration is a function of the initial concentration for the Athabasca River sediment. The tests with the shear stress of 0.259 N/m² (Test No. 4 and 6) also produced similar results. Such a behaviour is typical of cohesive sediments and conforms to earlier studies by a number of investigators such as Partheniades and Kennedy (1967), Mehta and Partheniades (1973) and Lick (1982). An explanation for such a behaviour was offered by Partheniades and Kennedy (1967). According to these authors, in cohesive sediment deposition process, there is no simultaneous erosion and deposition and the attainment of steady state concentration is due to the breakage and re-suspension of the weakly bonded flocs that cannot withstand the high shear stress in the flow region near the bed. In a given sediment mixture, there is only a certain fraction that can form stronger flocs and deposit. The remaining part consisting of the weakly bonded flocs stays in suspension. Therefore, the amount remaining in suspension is function of the initial concentration of the sediment. In a recent study, Lau and Krishnappan (1994) had confirmed that during cohesive sediment settling, there is no simultaneous erosion and deposition of sediment near the bed for a constant shear stress and provided support for the explanation put forth by Partheniades and Kennedy (1967).

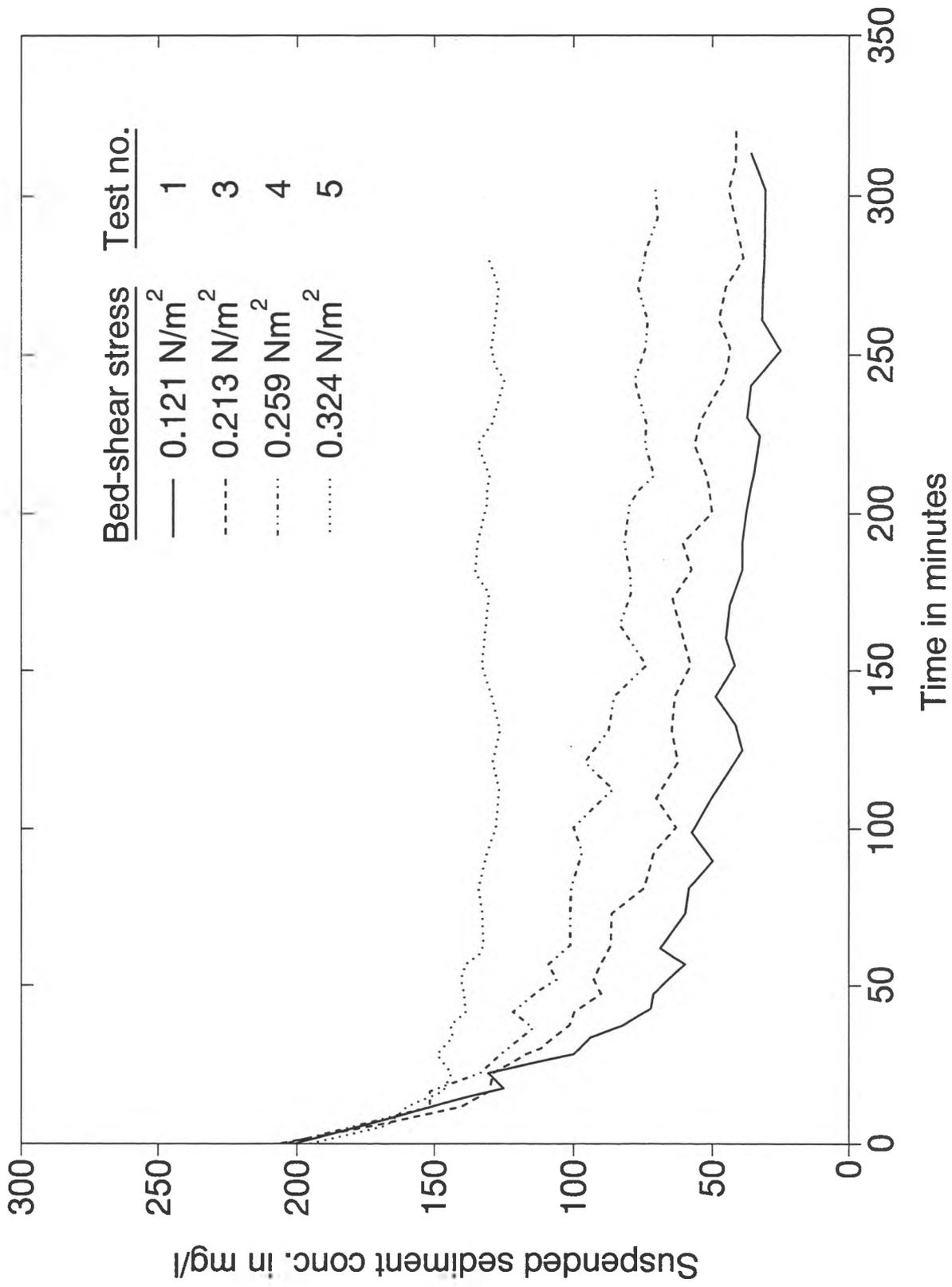


Fig. 4 Time variation of concentration of suspended sediment during deposition under different bed-shear stresses

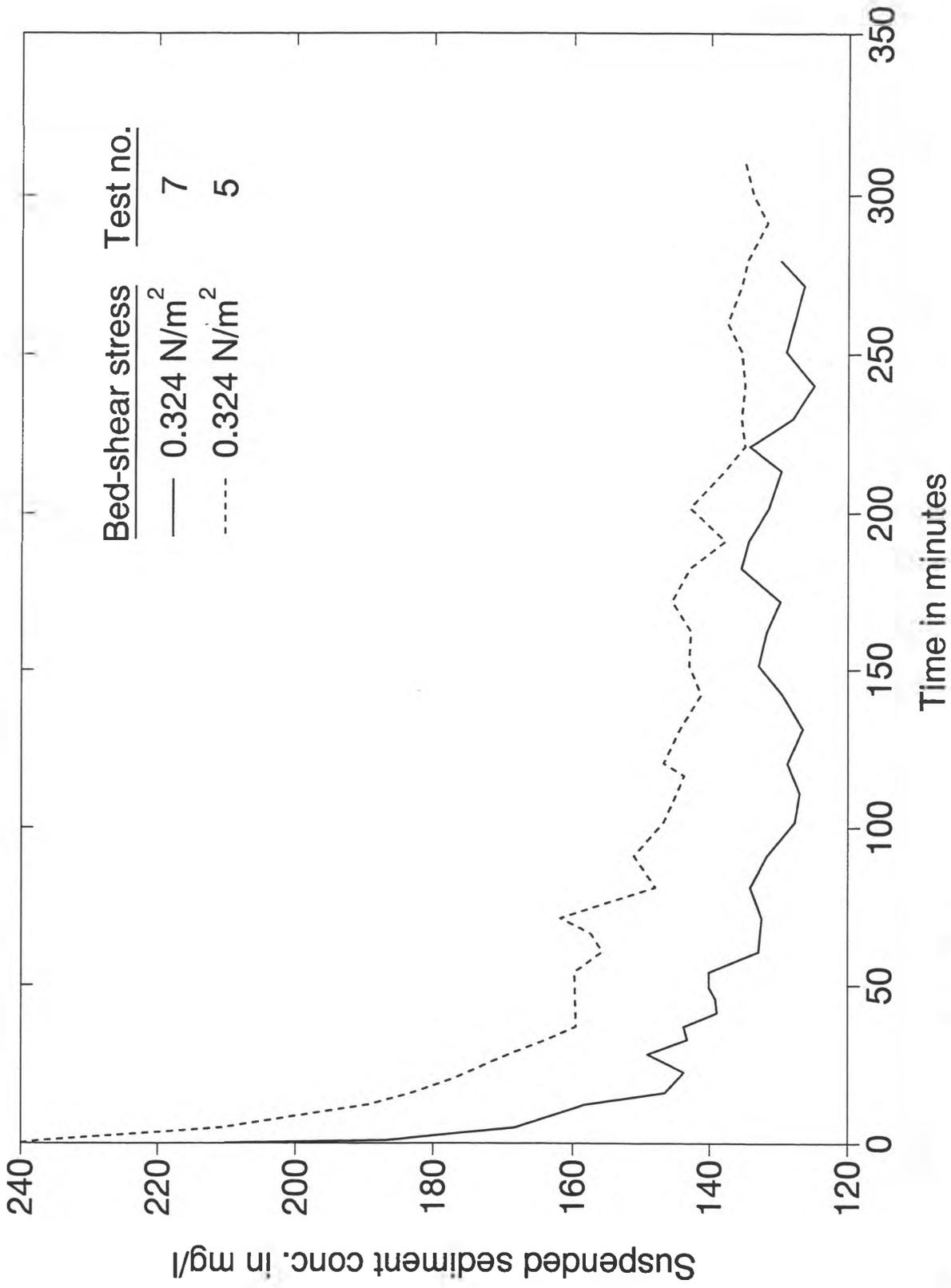


Fig. 5 Time variation of suspended sediment concentration during deposition under different initial concentrations

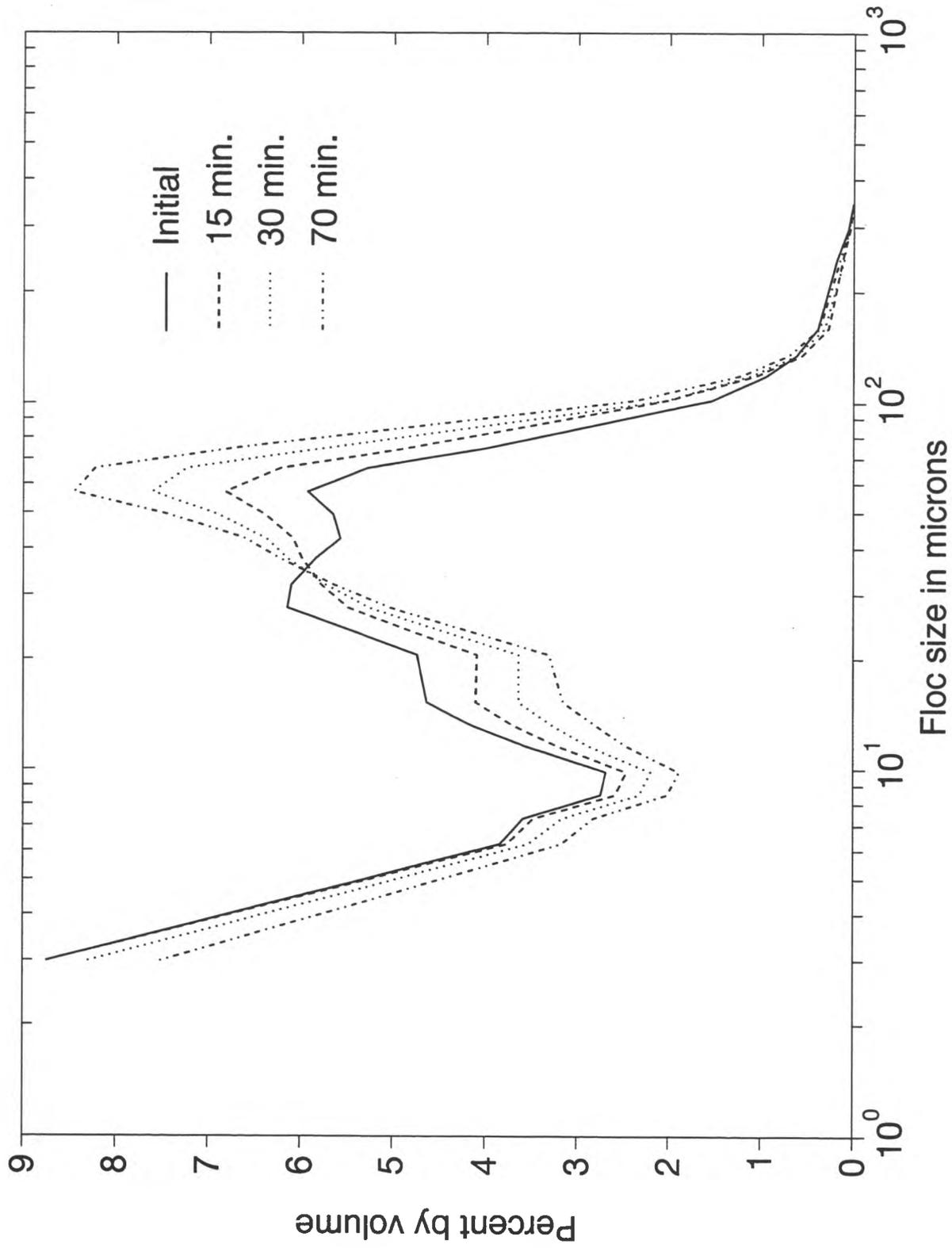


Fig. 6 Size distribution of suspended sediment flocs during deposition (Test no. 5; bed-shear stress = 0.324 N/m^2)

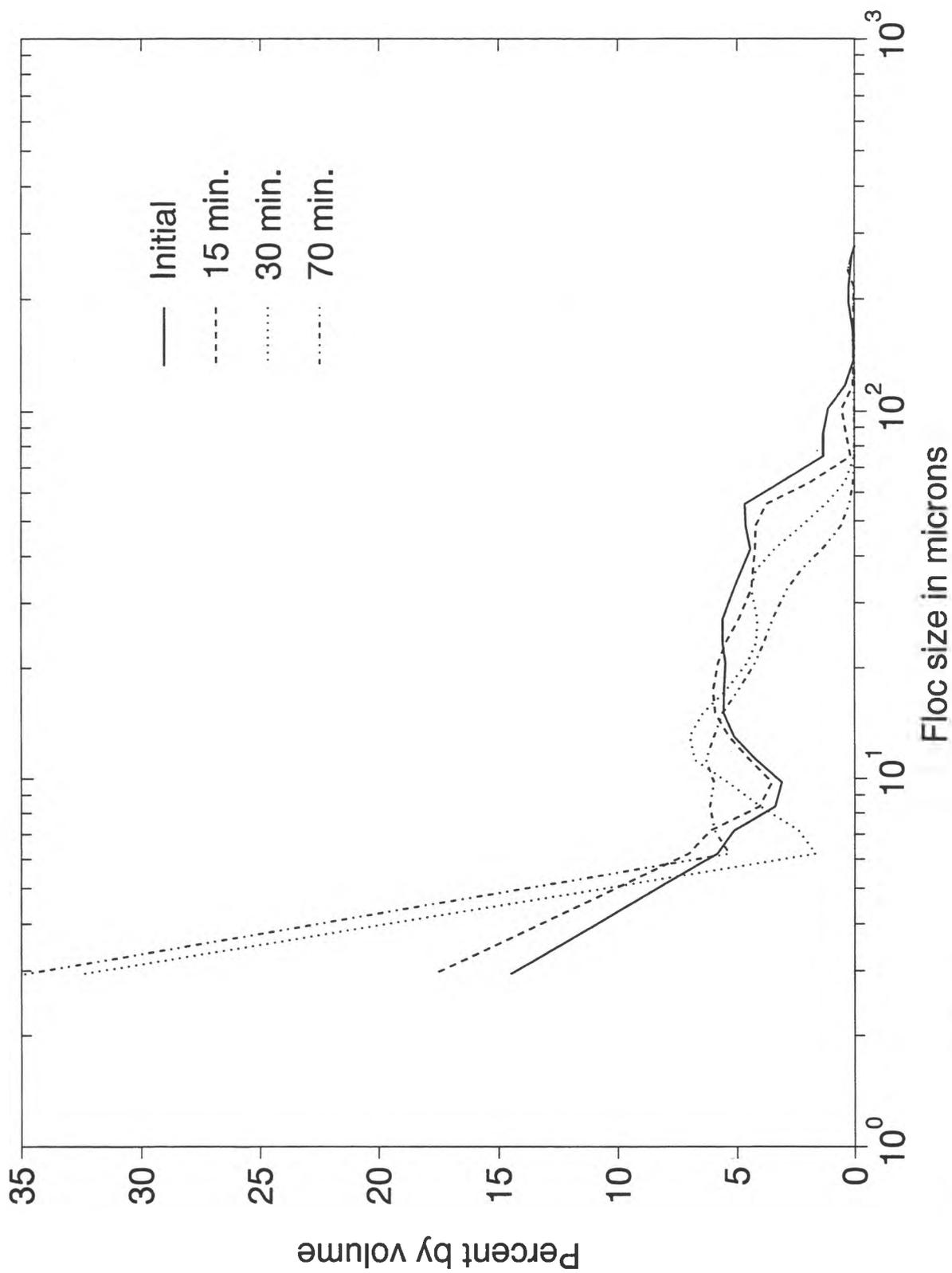


Fig. 7 Size distribution of suspended sediment flocs during deposition (Test no. 1; bed-shear stress = 0.121 N/m^2)

Flocculation of the sediment during deposition can be inferred from the size distribution data shown in Figure 6. In this figure, the size distribution of the sediment suspension as measured with the MPSA at different times during deposition for Test No. 5 are shown. During the initial mixing period, the weaker flocs are broken up and the suspension contains sediment flocs with a median size of about 26 microns. As the deposition begins, weaker flocs are reformed and the median size of the flocs increases as a function of time as shown in Figure 6. The process continues up to a period of 70 minutes, at which time, the flocs attain a steady state distribution with a median size of about 37 microns. This trend was common to all the runs that had shear stresses larger than 0.2 N/m². For tests with lower shear stress, i.e., for tests 1 and 2, the deposition of sediment continued without the formation of larger sediment flocs. This is due to lower sediment concentration in suspension and the decreased turbulence level. The size distribution pattern for Test no. 1 is shown in Figure 7 to illustrate this point. It can be seen from this figure that the size distribution becomes finer and finer as the time progresses due to settlement of the larger particles.

The effect of the pulp mill effluent on the deposition characteristics of the sediment is shown in Figures 8 and 9. In Figure 8, the time variation of suspended sediment concentration is plotted against time for two tests (for Test No. 6 and 8) with the same shear stress and initial concentration. In one of the two tests (Test No. 8), the pulp mill effluent was introduced at a concentration similar to that occurring in the river during low flow conditions (4% by volume). From this figure, it can be seen that the deposition rate for the Test No. 8 with the effluent is higher than that for Test No. 6 without the effluent. To make sure that the result is real, the Test No. 8 was repeated as Test No. 9. The results of Test No. 9 confirmed that the effluent effect was real and the test repeated itself with an error margin of 8%. In Figure 9, the size distribution of the suspended sediment flocs for the same two tests are shown at a particular time during the deposition process. From this figure also, it can be seen that the sediment flocs formed in the presence of effluent are larger. These findings are in agreement with the field observation that was carried out by Krishnappan et al. (1994) and a similar investigation that was carried out for the Fraser River sediment in the presence of pulp mill effluents (see Krishnappan and Engel (1994)). The results of the deposition experiments are summarized in terms of the steady state concentration in the following table below:

Table 2: Summary of results from deposition experiments. Steady state concentrations in mg/l.

| Shear stress in N/m ² | Initial Concentration in mg/l | | |
|----------------------------------|-------------------------------|------------------|--------------------------|
| | 200 | 250 | |
| | | without effluent | with effluent |
| 0.121 | 30 | | |
| 0.169 | 35 | | |
| 0.213 | 40 | | |
| 0.259 | 75 | 85 (Test 6) | 65 (Test 8); 70 (Test 9) |
| 0.324 | 130 | 140 (Test 7) | |

3.2 EROSION TESTS

The experimental conditions for erosion tests are given in Table 1. Three different consolidation times were tested. Results for all three tests were similar. Figure 10 shows the result for Test No. 11. In this figure, the shear stress steps and the corresponding concentration profiles are shown. The sediment deposit was completely stable until the bed shear stress reached a value of 0.169 N/m^2 , which can be considered as the critical shear stress for erosion. After that, the sediment bed started to erode and the concentration of sediment in suspension increased. At each shear stress step, sediment concentration increased gradually and showed a tendency to attain a steady state value similar to the erosion of cohesive sediment observed by other investigators such as Parchure and Mehta (1985) for much thicker beds. An increased shear strength in the interior of the bed was offered as an explanation for attaining the steady state concentration during erosion. An increased shear stress was needed to further erode the material. At the maximum shear stress of 0.520 N/m^2 , not all of the deposited sediment was re-suspended. The maximum concentration reached was only about sixty percent of the total concentration that would have resulted from complete re-suspension. The maximum concentration that was attained at the shear stress of 0.520 N/m^2 was about the same as the steady state concentration that resulted in a deposition test at a much lower shear stress of 0.324 N/m^2 . Note also that the critical shear stress for erosion is higher than the critical shear stress for deposition.

The size distribution of the re-suspended sediment measured during the erosion tests with the MPSA sheds some further light on the erosion process. From the size distribution data shown in Fig. 11, which corresponds to Test No. 11, it appears that the sediment bed is peeled off during the erosion process and the re-suspension contains a large percentage of larger flocs. As the bed shear stress is increased, the larger flocs break up and the distribution becomes finer.

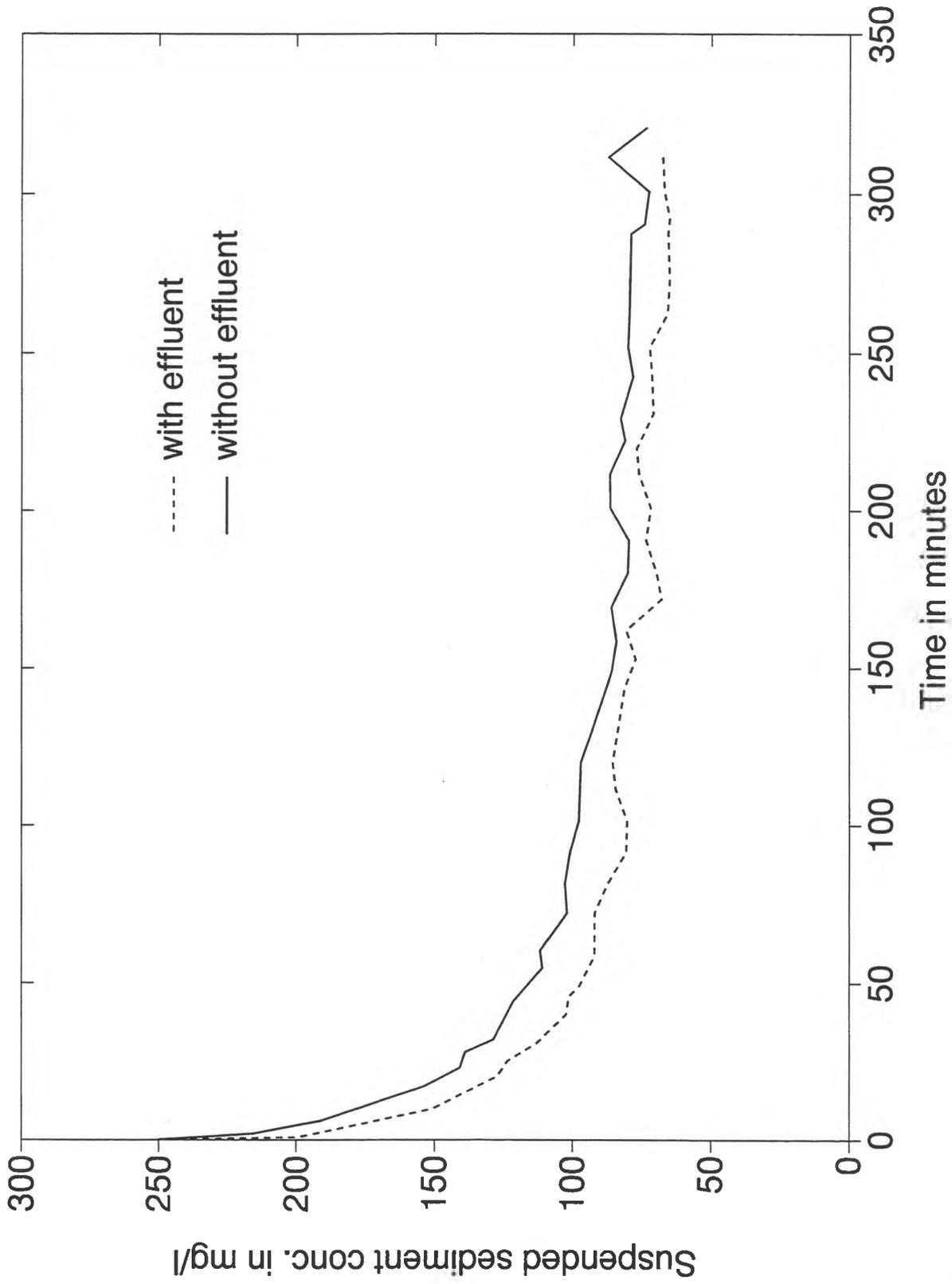


Fig. 8 Sediment concentration vs. time during deposition at a constant shear stress with and without pulp mill effluent

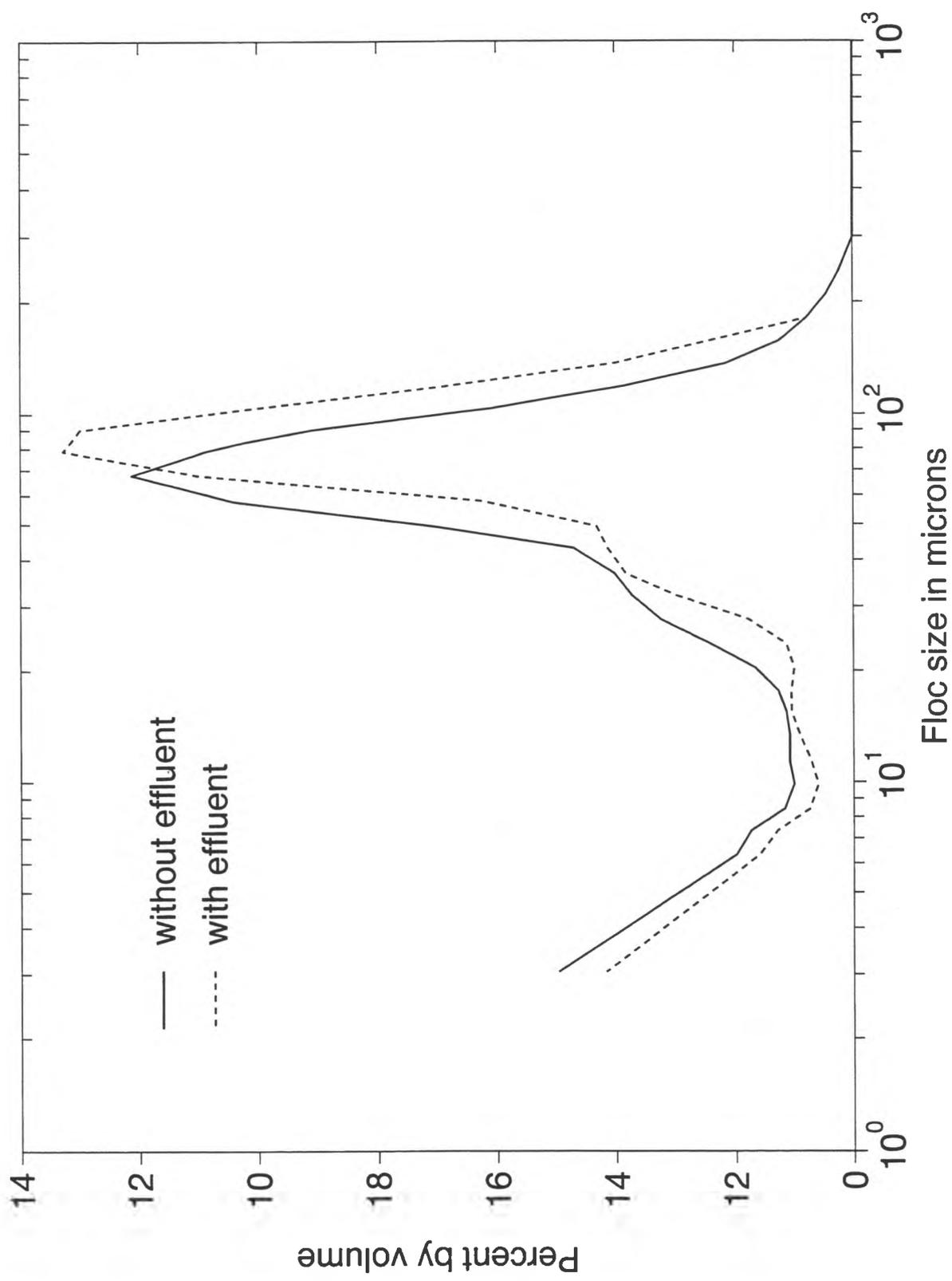


Fig. 9 Size distribution of sediment flocs with and without pulp mill effluent

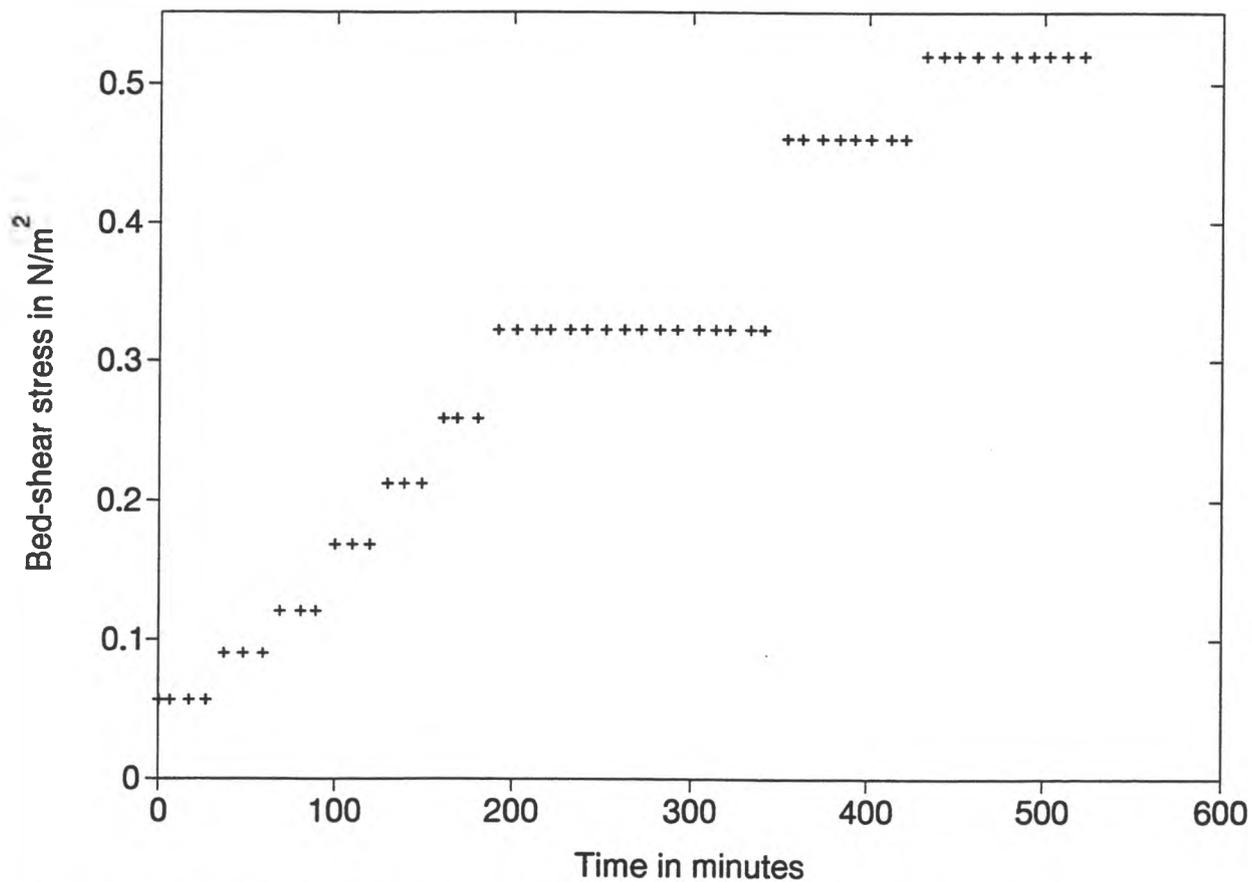
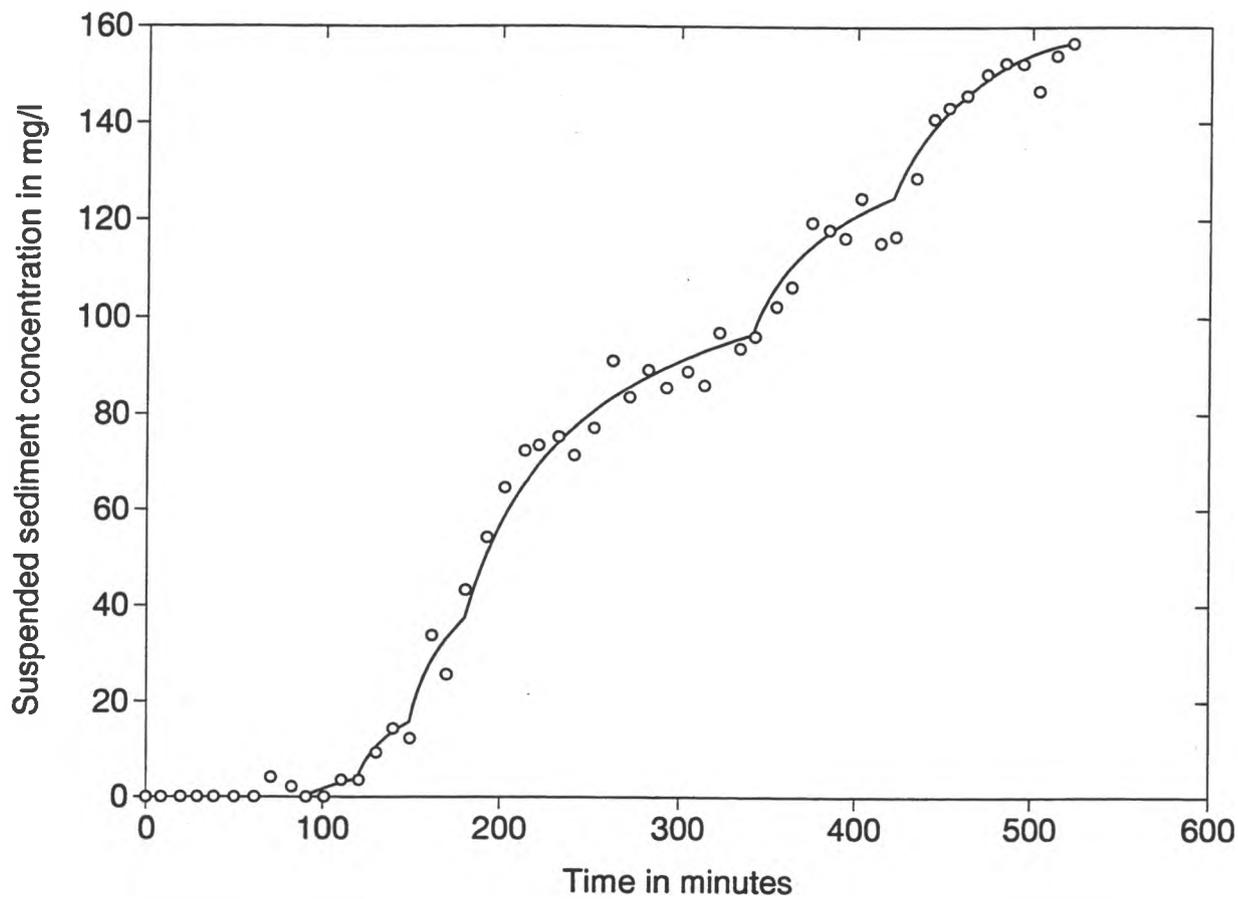


Fig. 10 Erosion characteristics of the deposited sediment for Test no. 11

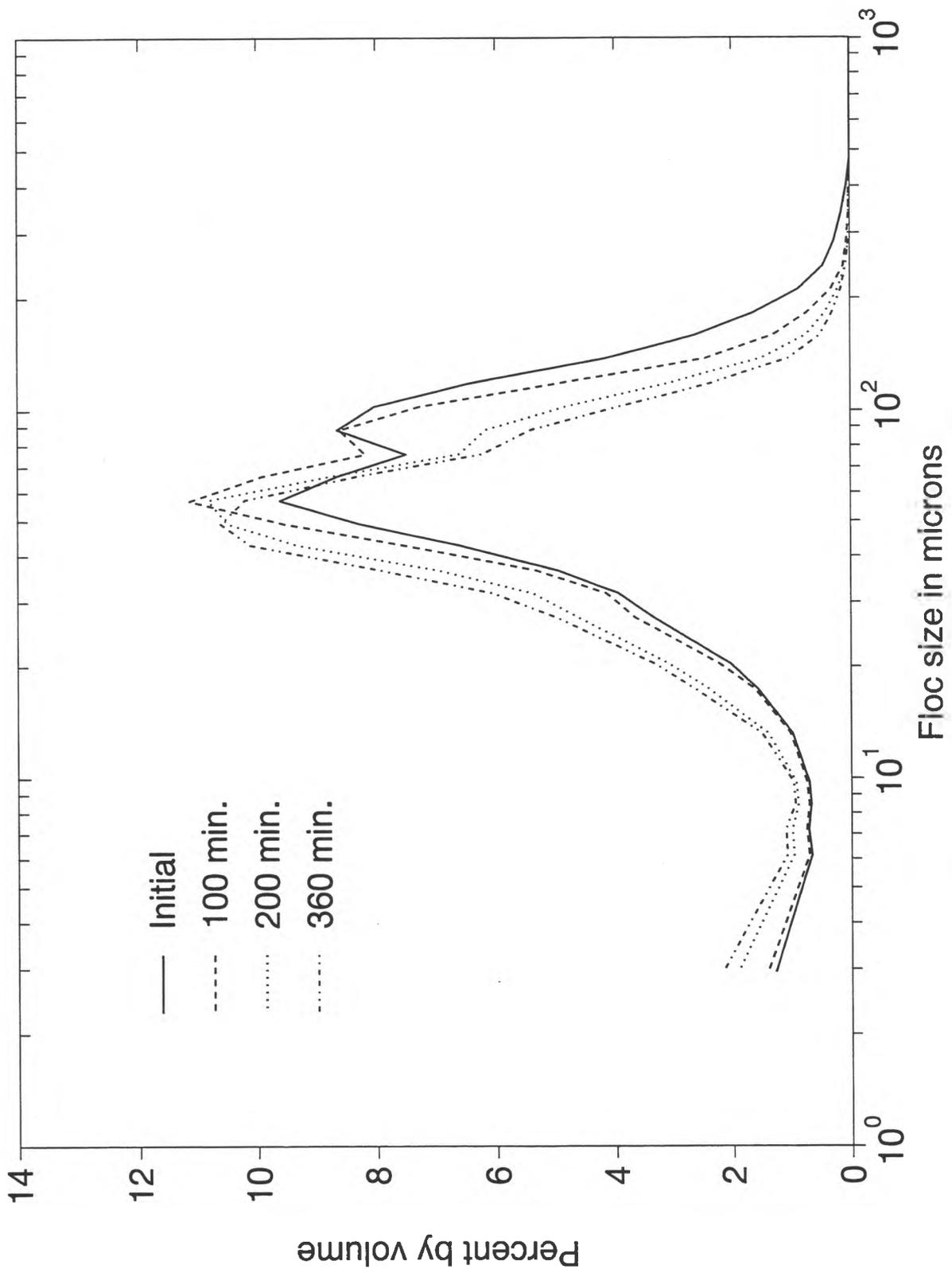


Fig. 11 Size distribution of eroded sediment in Test no. 11

3.3 APPLICATION TO THE ATHABASCA RIVER

The results from the present investigation were used to develop a new algorithm for the transport of fine sediment in the Athabasca River. The details of the new algorithm are summarized in Krishnappan (1995). The algorithm is being implemented in the WASP model that is being developed for predicting the impact of contaminants on the ecosystem of the Athabasca River as part of the Northern River Basins Study. For extrapolating the laboratory data to the field conditions, a scale relationship for the bed shear stress has to be developed to account for the difference in the flow characteristics near the bed in the laboratory channel and in the natural river. In the laboratory channel, the bed surface is smooth and the laminar sublayer that would form near the bed is several times larger than the sediment flocs that would deposit to the bed. Therefore, the sediment depositing to the bed in the flume is likely to be subjected to the laminar shear stress and the high velocity gradient within the laminar sublayer. In the natural river, on the other hand, the river bed is usually rough and the height of roughness elements could be several times larger than the thickness of the laminar sublayer. The sediment depositing in the river, therefore, is outside of the laminar sublayer and is subjected to the turbulent shear stress and the velocity gradient of the turbulent core. A scale relationship for the shear stress can be derived by equating the velocity gradient within the laminar sublayer to that of the turbulent core. The form of such a relationship is as follows:

$$\tau_{field} = \tau_{lab} \times 11.6 \times \kappa \quad (1)$$

where τ_{field} and τ_{lab} are shear stresses in the river and in the laboratory channel respectively and κ is the Von Karman constant. If we assume a value of κ as 0.40, then from the above equation, we see that the shear stress measure in the laboratory channel has to be multiplied by a factor of about five to obtain the shear stress in the field that would produce the same flow characteristics in the vicinity of the bed. The shear stress values so obtained cover a wide range of flow conditions that exist in the Athabasca River.

4.0 SUMMARY AND CONCLUSIONS

Deposition and erosion characteristics of the Athabasca River sediment were studied in a rotating circular flume. The influence of the pulp mill effluent from the Weldwood Pulp Mill at Hinton, Alberta on the deposition process of the sediment was also examined. The laboratory measurements provide quantitative information on critical shear stresses for erosion and deposition and, erosion and deposition rates as functions of time and bed shear stresses. The measurements also show that the sediment exhibits transport characteristics that are peculiar to cohesive sediments. The deposition process is dominated by the flocculation of the sediment and the pulp mill effluent further enhanced this process. The erosion process of the deposited sediment is characterized by the peeling off of the top layer of the sediment bed rather than by the mobilization of individual particles normally encountered in cohesionless sediment. The insights into the transport processes of the Athabasca River sediment gained through this investigation have led to the development of a new fine sediment transport algorithm that can be incorporated into ecosystem type models to predict the impact of contaminants in the Athabasca River.

5.0 REFERENCES

- Krishnappen, B. G., Stephens, R., Kraft, J. A. And Moore, B. H. 1994. Size distribution and transport of suspended particles in the Athabasca River near Hinton, NWRI Contribution No. 94-112, National Water Research Institute, Burlington, Ontario, Canada, 33p.
- Krishnappen, B. G. 1993. Rotating Circular Flume. *Journal of Hydraulic Engineering*. ASCE Vol. 119 No. 6, pp. 758-767.
- Krishnappen, B. G., Engel, P. And Stephens, R. 1994. Shear velocity distribution in a rotating flume. NWRI Contribution No. 94-102, National Water Research Institute, Burlington, Ontario, Canada, 23p.
- B. G. Krishnappen and P. Engel. 1994. Critical shear stresses for erosion and deposition of fine grained sediment in the Fraser River. Proc. 4th Nearshore and Estuarine Cohesive Sediment Transport Conference, INTERCOH'94, Wallingford, England.
- B. G. Krishnappen. 1995. A new algorithm for fine sediment transport. Report under internal review.
- Lau, Y. L. And Krishnappen, B. G. 1994. Does reentrainment occur during cohesive sediment settling? *Journal of Hydraulic Engineering*, Vol. 120, No. 2, pp.236-244.
- Lick, W., 1982. Entrainment, deposition and transport of fine grained sediments in Lakes. *Hydrobiologia*, Vol. 91, pp. 31-40.
- Mehta, A. J. And Partheniades, E. 1973. Depositional behaviour of cohesive sediments. UFL/COEL-TR/016, Coastal and Oceanographic Engineering Department, University of Florida, Gainesville, Florida, 297p.
- Parchure, T. M. And Mehta, A. J. 1986. Erosion of soft cohesive sediment deposits. *Journal of Hydraulic Engineering*, Vol. 111, No. 10, pp. 1308-1326.
- Partheniades, E. And Kennedy, J. F. 1967. Depositional behaviour of fine sediment in a turbulent fluid motion. Proc. 10th Conference on Coastal Engineering, Tokyo, Japan. Vol. 2. Pp. 707-729.
- Patel, V. C. 1965. Calibration of the Preston Tube and Limitations on its use in Pressure gradients. *Journal of Fluid Mechanics*, Vol. 23 No. 1, pp. 185-208.
- Petersen, O. And Krishnappen, B. G. 1994. Measurement and analysis of flow characteristics in rotating circular flume, *Journal of Hydraulic Research, IAHR*, Vol. 32, No. 4, pp. 483-494.
- Weiner, B. B. 1984. Particle and droplet sizing using Fraunhofer Diffraction. *Modern Methods of Particle Size Analysis*, H. G. Barth (ed.), John Wiley and Sons, New York, N. Y., 135-172.

APPENDIX A

TERMS OF REFERENCE

NORTHERN RIVER BASINS STUDY

APPENDIX A - TERMS OF REFERENCE

Project 1332-C1 Effects of Flocculation on the Erodability and Critical Shear Stress of Deposited Suspended Sediment

Objective

To supply the fine sediment transport parameters to the existing sediment bound contaminant transport models and to improve the formulation of fine sediment transport models by incorporating the flocculation processes (relevant to Scientific Questions #5 and #14 and related to Flow Hydrology/Hydraulics and Sediment Transport and Contaminant study groups).

Description

The sediment transport component of contaminant transport models such as WASP-4, TABS-2, FETRA etc. require input data on sediment parameters such as the erodability factor and the critical shear stresses for erosion and depositional processes. These parameters depend upon the flocculation mechanism which in turn depends upon a large number of variables characterizing the bed shear stress, sediment and fluid composition and bed structure. Therefore, these parameters cannot be estimated from literature studies. One possibility is a direct measurement in a rotating flume using site specific sediment-water mixtures.

The Rotating flume recently installed at the National Water Research Institute in Burlington will be used to measure these parameters for the suspended sediments of the upper reaches of the Athabasca and Peace Rivers near the pulp mills. The flume is 5.0 m in mean diameter, 0.30 m in width and 0.30 m in depth and it rests on a rotating platform. A counter rotating top cover fits inside the flume and makes contact with the water surface and generates the shear flow. The details of the flume and the description of the instruments can be found in Krishnappan (1991). To perform the tests, 1000 litres of river water will be brought to the laboratory. The sediment-water mixture will be placed in the flume and will be subjected to different shear stresses and the appropriate measurements will be made to estimate the required parameters. From the results of the experiments, attempts will be made to improve the formulation of the sediment transport model.

References

Krishnappan, B. G. A Rotating Flume for Cohesive Sediment Transport Research, paper accepted for publication in the Journal of Hydraulic Engineering, American Society of Civil Engineers.

3 1510 00168 3342
