National Library of Canada
Acquisitions and Bibliographic Services Branch
395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale du Canada
Direction des acquisitions et des services bibliographiques
395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Your file Votre référence

Our file Notre référence

NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30, et ses amendements subséquents.

Canada

UNIVERSITY OF ALBERTA

GEOTECHNICS OF NON-SEGREGATING OIL SAND TAILINGS

BY

DAVID L. CAUGHILL ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of MASTERS OF SCIENCE.

IN

GEOTECHNICAL ENGINEERING

DEPARTMENT OF CIVIL ENGINEERING

EDMONTON, ALBERTA

FALL 1992

ISBN 0-315-77283-2

UNIVERSITY OF ALBERTA

RELEASE FORM

NAME OF AUTHOR: David L. Caughill

TITLE OF THESIS: Geotechnics of Non-Segregating Oil Sand Tailings

DEGREE: Masters of Science

YEAR THIS DEGREE GRANTED: 1992

David Caughill

David L. Caughill
10929-74 Avenue
Edmonton, Alberta T6G 0E5

July 21, 1992

UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled GEOTECHNICS OF NON-SEGREGATING OIL SAND TAILINGS submitted by DAVID L. CAUGHILL in partial fulfillment of the requirments for the degree of MASTERS OF SCIENCE in GEOTECHNICAL ENGINEERING.

Dr. N.R. Morgenstern

J. D. Scott
Dr. J.D. Scott

Dr. N. Rajaratnam

Dr. A. Pierre

June 22, 1992

Abstract

The present method of oil sands tailings disposal results in a tailings pond with a fine tails zone that will take many decades to fully consolidate. Non-segregating mixes of total tailings are desired to prevent or greatly reduce the formation of a fine tailings zone. Lime and sulphuric acid were used in this study to prevent segregation of the tailings. Two batches of total tailings from the Syncrude Canada Ltd. operation were tested. These averaged 48 % solids and 55 % solids, with an average fines content (< 44 microns) of 17 %. The settlement and consolidation properties of non-segregating mixes were determined using large diameter standpipe and slurry consolidation tests. Based on these tests, non-segregating mixes were achieved by adding 600 to 800 ppm CaO, based on the total weight, or 7.5 to 10 ml/l of 10 % H_2SO_4, based on the total volume of tailings. A significant volume reduction (30 to 40 %) occurred in the first few days after deposition due to hindered settling of the treated tailings. Self-weight consolidation, with effective stresses of 5 to 10 kPa, results in tailings with a predominantly sand structure, after a longer time period. Further testing is required to determine the concentration of additives required for tailings with lower and higher solids and fines contents. As well, the effect of increasing shear on the segregation of the mixes needs to be determined.

Acknowledgements

The friendly guidance of Dr. N.R. Morgenstern and Dr. J.D. Scott throughout the work of this thesis and beyond is gratefully acknowledged.

The unfailing help of the technicians Gerry Cyre, Steve Gamble, Christine Hereygers and Jay Khajuria, without which I would still be working in the lab, is also gratefully acknowledged.

I would like to thank Syncrude for kindly supplying the tailings for the thesis work.

I would also like to acknowledge the financial assistance provided to me, during the thesis work, by Dr. Morgenstern's NSERC grant - OGP 7063.

Table of Contents

List of Tables

List of Figures

1. Introduction

1.1 Statement of Problem

The Athabasca oil sand deposit of northern Alberta is mined and processed to produce synthetic crude oil. The resulting tailings stream is pumped to a tailings pond where the sand that settles out of the tailings stream is used to form a containment dyke. The dyke is used to contain the fine portion of the tailings, a large portion of the tailings water and most of the bitumen not recovered in the processing plant. This combination of fines, water and bitumen consolidates very slowly, on the order of decades, resulting in a long-term disposal problem.

It is suggested that if the tailings stream can be made non-segregating by using additives to flocculate or coagulate the clays, the tailings pond can be eliminated or greatly reduced in size. The non-segregating tailings can be deposited in layers in the existing pit or within dykes built on the surface and reclaimed once the containment area is full.

1.2 Objectives of Research

The purpose of the work in this thesis is to determine the effectiveness of lime, of lime and a high molecular weight polymer and of sulphuric acid to prevent segregation of total tailings and if successful, to study the geotechnical properties of the resultant materials.

The main objective is to determine the concentrations of additives to prevent segregation and then the optimum concentrations of additives in terms of the settlement and consolidation properties of the mixtures.

Additional objectives are to determine the hindered settling rate, and the consolidation parameters (void ratio with effective stress) and (hydraulic conductivity with void ratio) of the non-segregating mixtures. Included with this are the development of laboratory equipment and procedures to achieve these objectives.

The final objective is to use the laboratory parameters to predict settling and consolidation rates in the field, using hindered settling and finite strain consolidation theories.

1.3 Scope of Thesis

Standpipe tests are used to determine the hindered settling and self-weight consolidation properties of non-segregating mixes of tailings. The standpipes range in height from 0.35 m to 2.0 m. The tailings range from 45 to 55 percent solids and 15 to 20 percent fines based on the #325 (44 micron) sieve.

The consolidation properties are determined using both large scale step load and constant rate of deformation consolidation equipment. Permeability measurements are performed between the increments of the step load consolidation test.

The laboratory data of void ratio versus time, void ratio versus effective stress and void ratio versus hydraulic conductivity are used in a finite strain consolidation program to predict the rate of consolidation of tailings with time in the field.

1.4 Organization of Thesis

Chapter 2 contains a review of literature relevant to this thesis. The oil sands operations are first reviewed, followed by a review of any work performed on treatment of oil sand tailings. The other topics reviewed are: 1) the use of flocculants and coagulants in other industries, 2) clay aggregation by flocculants and coagulants, 3) batch mixing equipment and theory, 4) hindered settling and finite strain consolidation testing and theory.

The testing program is described in chapter 3. This includes a description of the equipment used and the testing procedures, including the tailings and flocculant preparation procedures.

The results of the testing program are presented in chapter 4. This has two major sections, one for each batch of tailings. The supernatant water chemistry results are presented in the last section of the chapter.

Chapter 5 contains the field predictions based on the experimental data obtained in the thesis work.

The conclusions and recommendations for further work, based on the findings in this research program, are presented in chapter 6.

2. Literature Review

2.1 Overview of Oil Sands Operations

The oil sand deposits of Canada are located in the northern half of Alberta. The largest are the Athabasca, Peace River and Cold Lake deposits, as shown in Figure 2.1. The three deposits contain approximately 266 billion m^3 (1673 billion barrels) of crude bitumen, in-place (ERCB, 1990). The largest of the deposits, the Athabasca, is the only one with shallow enough overburden to allow surface mining. It is estimated that the proved synthetic crude oil reserves from the surface mining areas of this deposit would be 4.8 billion m^3 (30 billion barrels) (ERCB, 1990).

At present, there are two commercial operations, both mining the oil sands from the Athabasca deposit near Ft. McMurray, Alberta. These are the Syncrude Canada Ltd. and Suncor Ltd. operations. Both use surface mining techniques to extract the oil sand, the modified hot water extraction process to extract the bitumen and tailings ponds to store the tailings after the extraction process. Combined, the plants produce approximately 33,000 m^3/d (208,000 barrels/d) of synthetic crude oil or approximately 20 % of Canada's domestic production (ERCB, 1990).

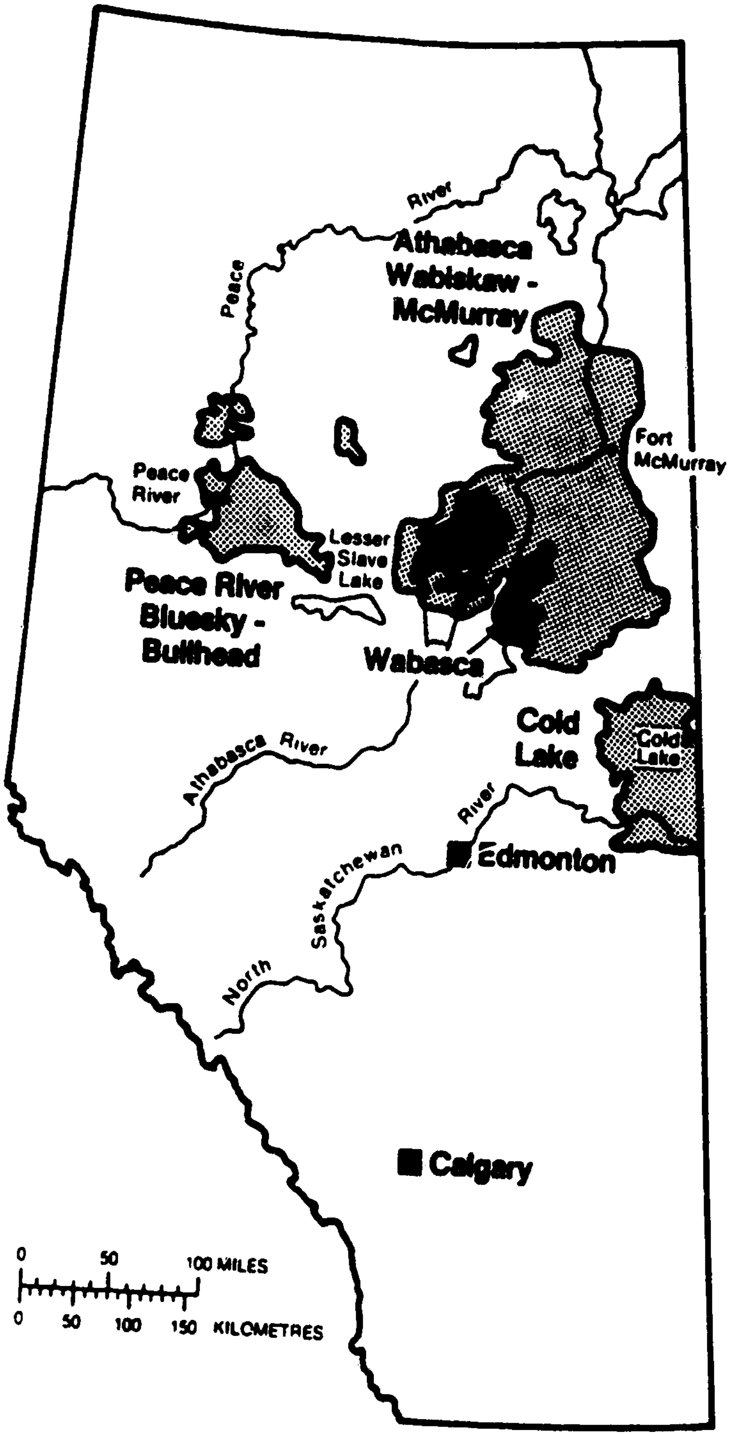


Figure 2.1 Map of Oil Sand Deposits in Alberta

In situ, the oil sands consist of predominantly quartz sand grains, surrounded by a thin film of water and fines, with the remaining pore space filled with bitumen and some associated gas (Fig. 2.2, after Dusseault, 1977). The majority of fines in the deposits are found in separate seams and lenses, often containing thin micaceous partings. The composition of the Athabasca deposit averages 5 % water, 11 % bitumen, 12 % fines (< #325 sieve) and 72 % sand, based on the total mass. The largest variation in the ore stream is with the amount of bitumen and the amount of fines (Dusseault and Scott, 1983).

The extraction process consists of several stages. The first conditioning stage involves adding hot water to the oil sand ore and then charging with steam at 80 to 95 °C. Sodium hydroxide is added to increase the pH to 8.0 to 8.5 to disperse the clays, allowing the bitumen to be removed from the solids more easily. This results in the fines being dispersed into the water medium.

In the next stage, called the separation stage, more water is added to the tailings to promote segregation so that the bitumen will float to the surface as a froth. The froth is skimmed off the surface and the bitumen recovered. The coarse solids sink to the bottom of the vessel where they are drained off. The remaining material is called the middle zone or middlings. It consists of water, dispersed clay and bitumen. This zone is drawn off, and air flotation is used to remove more of the bitumen. This stream is then

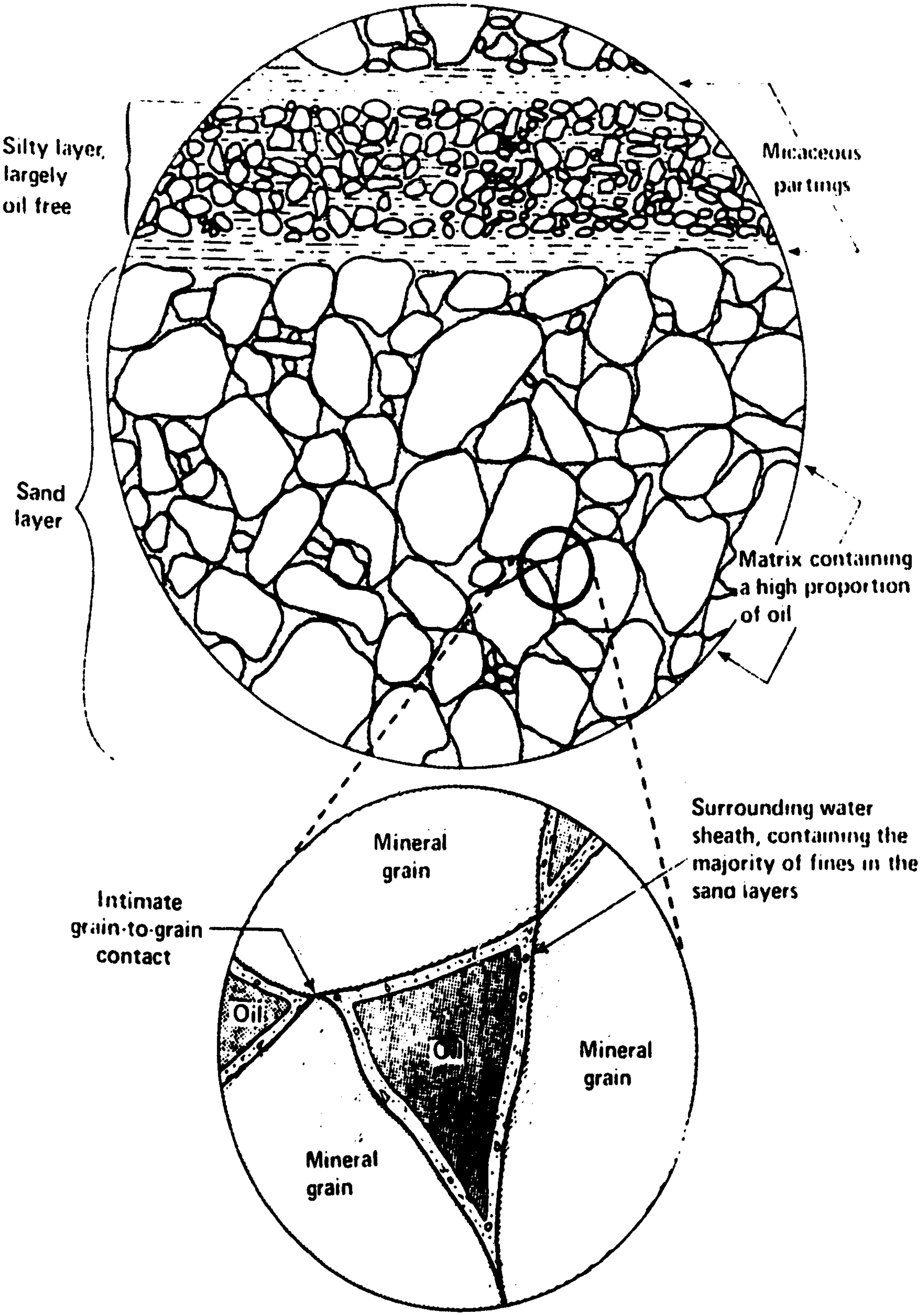


Figure 2.2 Composition of Oil Sand (after Dusseault, 1977)

combined with the coarse solids stream to form the tailings stream (Camp, 1977). Additional water (level control water) is also often added to the tailings to allow them to be pumped more efficiently. At Syncrude, 117 x 10^6 metric tonnes of oil sand ore are mined annually, resulting in 98 x 10^6 tonnes of tailings solids per year (Syncrude - personal communication, 1991).

The average tailings stream consists of approximately 1 % bitumen, 17 % fines and 82 % sand (based on dry weight). The fines content varies from about 8 % to 25 % as the plant feed varies. The fines content in this research is based on the #325 sieve (44 microns), and about 45% of the fines are clay size (<2 microns). The solids content of the stream ranges from about 35 % to 65 %, with an average of about 55 %. The clay fraction consists predominantly of kaolinite and illite, with some minor amounts of montmorillonite. The sand is uniform around the 150 micron size.

The high water content of the tailings stream is advantageous in that it can be hydraulically transported. This is the most efficient method of tailings transportation. As noted, extra water is generally added to the tailings stream to obtain a mix that can be hydraulically transported more efficiently.

The disadvantage of the tailings stream is that it segregates upon disposal. This results in a predominantly sand beach around the outside of the tailings pond and a very high water content fines zone in the centre of the pond. The sand is used to construct the dyke that contains the fines zone. This fines zone takes several years to settle and consolidate to a 30 to 35 % solids content. It is believed that any consolidation beyond this stage occurs at a very slow rate. Consolidation of the sludge to a reclaimable state could take tens of decades. As a result, bulking of the tailings occurs to about 1.4 times that of the oil sand ore (Camp, 1977; Scott and Dusseault, 1980).

Segregation of tailings creates an environmental as well as an operational problem. Environmentally, the pond is a problem because it is not a permanent disposal solution. The pond is toxic to any wildlife and ensuring the stability of the pond for the very long term is a problem. Operationally, it is a problem because Syncrude plans to mine the area beneath the pond sometime in the future.

Any solution to the tailings problem should ideally include hydraulic transportation, one-step disposal, a reclaimable surface, low cost and high safety, reclaim of water, leachate control and a reduction in total storage volume.

2.2 Treatment of Oil Sand Tailings

There has been a considerable amount of work on the tailings problem, with most of it concentrated on the fines portion of the tailings stream. Most of the laboratory work was performed on fine tailings dredged from the centre of a tailings pond, with some work on total tailings sampled from a tailings line.

Some of the work performed on total tailings involves flocculating the clays to achieve a non-segregating tailings stream. Generally settlement and occasionally consolidation tests were performed on tailings treated with a flocculant. Papers are presented in section 2.2.1 and patents in section 2.2.2, in chronological order.

2.2.1 Papers

Hocking and Lee (1977) treated fine tailings with electrolytes, acids, oxidizing and reducing agents and organic flocculating agents. The settlement characteristics were determined using a centrifuge. Hydrochloric acid and sulphur dioxide were found to work the best, with electrolytes and oxidizing agents next. The problem with the experiments was that a centrifuge was used to determine the settlement characteristics, which because of the very high stresses present, make it very difficult to compare to self-weight experiments with very low stresses.

Rao (1980) performed small scale tests on the short term settlement and drainage behaviour of fine tailings flocculated with polyacrylamides after pretreatment with electrolytes. The tests were performed on Syncrude and Suncor fine tails samples of 10 % and 16 % solids content respectively.

The electrolytes used for pretreatment were $CaCl_2$, $MgSO_4$, $CaSO_4$ and CaO. The flocculants used were Percol 140, a high molecular weight cationic polyacrylamide (PAM), Percol 351, a very high molecular weight non-ionic PAM, Separan MG 200, a high molecular weight anionic PAM and Cyanamid A-130, a high molecular weight anionic PAM. Cyanamid A-130 was found to work the best in terms of the amount of settlement and % fines in the decant. The best electrolytes were $CaCl_2$ and $MgSO_4$, followed by CaO.

The results are useful for suggesting which chemicals work the best, but since the tests were so small (0.48 litres) and short term (1 day) no conclusions in terms of the geotechnical properties of the samples can be drawn.

In a report for AOSTRA, Erno and Hepler (1981) investigate the use of various flocculating agents to enhance the use of pressure filtration on whole oil sand tailings. The principle scheme involved adding lime to the total tailings until a pH of 11.8 was reached (with an associated increase in viscosity), then adding an ionic flocculant, a neutral flocculant and then dewatering by pressure filtration. It was mentioned that the flocculants may not necessarily be required. CaO worked well for high solids content tailings, but addition of ionic flocculants worked better for lower solids content tailings.

It was found by testing a number of flocculants that Cyanamid A-130 worked well with CaO. It was also found that sulphuric acid would also work, but not as well as lime for filtration. The amount of lime required increases with the solids content of the tailings and is also related to the bicarbonate content and the cation exchange capacity of the clays.

A paper and a patent by Kessick (1982) refer to the use of polyacrylamide in combination with calcium ions to flocculate clays in oil sands fine tailings. This method can be used to enhance the recovery of bitumen from the fine tails. Disposal techniques revolve around disposal of the clay fraction. Calcium treatment of clay tailings before adding polyacrylamide enhances the flocculation caused by the polyacrylamide. The flocculation is caused by bridging of the polymers across clay particles and seems to be enhanced by the organic component of the sludges. In the first stage, lime is used to cause a water-in-oil emulsion allowing bitumen removal. In the second stage lime and polymer could be used for dewatering the resulting clay suspension by flocculation. This method could be used for treatment of either fine tailings from the pond or as a part of the recovery process. Disposal of the tailings stream is not included as part of the exclusive privilege.

In a report for Environment Canada, C-H Synfuels (1984) study the potential of flocculating or coagulating whole tailings and then depositing the resultant material using a method similar to Robinsky's thickened discharge method (Robinsky, 1978). The chemicals tested were lime, Cyanamid high molecular weight anionic polymers (Magnifloc A-110 and

A-137) and $FeCl_3$. The majority of the testing was performed using lime and the polymer A-110, as it was found that the other chemicals showed no advantage in use.

The report includes a review of the oil sands, oil sand processing and the tailings problem. The testing was performed in 1.5 litre jars and 4 liter 3 m high columns (5 cm diameter). From the jar tests an optimum lime concentration of about 600 ppm CaO based on the total weight of the sample and an optimum lime plus polymer concentration of 550 ppm + 6 ppm based on total weight were determined. The settled average void ratio using these concentrations is around 1.0 based on the water content, although there are some contradictions to this in the report. A problem with these tests is that properties of the material such as initial solids content, specific gravity and grain size are not reported, making it difficult to compare these results to those found in the author's research program.

One useful result is that one test with 585 ppm CaO and 2 ppm A-110 was performed at 69 °C as opposed to the 20 °C used for the rest of the tests. The test showed a faster settlement rate for the 69 °C test, but no change in final settlement amount. The increase in settlement rate was attributed to a lower viscosity of the water at the higher temperature. It was also noted that more oil floated on the surface of the sample than for the 20 °C tests.

Small scale flume tests were also performed as part of the study. It was found that higher lime concentrations were required to prevent the tailings from segregating in the flume (1000 - 1500 ppm). They postulate that this may be due to air entrapped in the sample during the mixing process, but no testing was performed to prove this.

Chemical analysis was also performed on the decant water from the tests and these results will be compared to the ones of this study in section 5.3.

The report also includes sections on a water recycle scheme, a proposed disposal concept, a limited economic study and a reclamation study. The report is labelled as a preliminary report and as such is inconsistent in a few places, but a valuable starting point to compare the results of this thesis.

A report by Marsh and Shaw (1984) presents a study of the fines capture achieved on deposition and the beach formation of segregating and non-segregating oil sand slurries. Tailings of various fines and solid contents were prepared by mixing sand and fine tails. 1000 ppm lime (not defined) was added to four tests with high fines contents. Lime was found to reduce the beach slope, but did not completely prevent segregation in the flume.

Prasad and Joshi (1985) added lime to sludge and then used the centrifuge to analyse the effectiveness of lime for removing bitumen from the sample. No total tailings were tested and since only centrifuge tests were done, this will not be discussed further.

Scott and Chichak (1986) determined the minimum concentration of CaO, Ca(OH_2), $CaCl_2$, H_2SO_4 and $CaSO_4 \cdot 2H_2O$ to prevent segregation in standpipes and troughs and the self-weight consolidation characteristics of the non-segregating mixes. The tailings tested was a mixture of fine tails, tailing pond water and beach sand, resulting in a tailings with 54 % solids and 20 % fines (< 44 microns). The cylinders used for the test were 90 cm high and 7.5 cm in diameter and the troughs were 2.4 m long, 30 cm wide and 30 cm high. It was found that concentrations of 750 ppm CaO prevented segregation in both the standpipes and the trough and 300 ppm H_2SO_4 prevented segregation in the standpipes (trough tests were not performed for the acid).

2.2.2 Patents

Elliot (1975) incorporates freeze-thaw of tailings after adding an agglomerating agent. Agglomeration can be caused by either raising the pH to over 9.0 using a basic reagent or lowering to below 7.5 using an acidic reagent. The reagents listed include CaO and other calcium sources as well as high molecular weight acrylamide polymers.

Lang and Hentz (1973) treat tailings by flocculating using an acrylic acid or water soluble acrylic acid derived polymer and using a non-ionic polymer as a secondary flocculant. There is no mention of a disposal technique in the patent.

Baillie and Fear (1976) suggest spraying total tailings over the pond area to use the sand to increase the rate of consolidation of the sludge in the pond. No additives are discussed.

Behan and Vendrinsky (1976) use an alkaline reagent and then sulfuric acid to break up emulsions formed by adding NaOH to the tailings stream to allow bitumen to be recovered.

Bain and Roberts (1977) outline a method of mixing sludge with the total tailings stream and depositing the mixture over an inclined sand pile with water above. No additives are discussed.

Schutte (1977) uses acid (specifically sulphuric acid) to clarify middlings water from oil sands processes. The acid causes the clays to flocculate and thus settle by lowering the pH to the range 5.5 - 7.0. The pH is claimed to return to essentially neutral conditions after sitting for a few days. The method is claimed to work for waters containing up to 10 percent solids by weight. It is not discussed whether the method would work for total tailings.

Specken (1977) adds finely divided activated carbon to sludge to adsorb toxic compounds, then adds coagulating agent (calcium ion), flocculating agent (commercial flocculation agent) and sodium bentonite to cause flocculation of the fines in drilling fluid sumps or oil sands tailings. It was found that two stage addition of polyelectrolytes would give rise to tighter flocs. It was also found that for some waste fluids, adding a strong oxidant such as potassium permanganate leads to a pronounced reduction in the amount of flocculant dosage required. It was suggested that a floating aerator could be used to disperse the chemicals into the fluid. There is no mention of total tailings or deposition method for total tailings in the patent.

Tibbitt (1977) suggests adjusting the pH and then freezing and thawing the water effluent or sludge from oil sand tailings. The material stream is divided into two parts, with the pH of one stream raised above 8.5 by adding a basic reagent and the pH of the other stream lowered below 7.5 by adding an acidic reagent. The streams are then combined and allowed to freeze and thaw. It is claimed that less basic and acidic reagents are required for the same results than if only an acidic reagent was added and also the resultant pH would be more neutral. There is no mention of specific reagents or of total tailings or deposition schemes.

Specken (1978) uses an alkali permanganate and polyelectrolyte to flocculate the clays in a drilling fluid sump or oil sands tailings stream. There is no mention of total tailings or deposition method in the patent.

Liu, Lane and Cymbalisty (1980) suggest a method to treat tailings before vacuum filtering. The clay is flocculated using lime as a 10 % by weight slurry and then filtered. CaO was found to work well in 300-700 ppm by total weight range. Other salts such as $CaCl_2$, $Al_2(SO_4)_3$, $FeCl_3$, $CaSO_4$ were tried, but CaO was found to be the most desirable in terms of performance and cost. The patent describes ways of mixing CaO and water and pumping the mixture into the tailings, but no deposition schemes are mentioned.

Fuhr and Liu (1981) suggest a method for controlling flocculant addition to a tailings stream by monitoring the zeta potential. Lime (at a 10 % by weight slurry) is added to the tailings stream until the zeta potential equals zero then the solids and water are separated by vacuum filtration. Tests have shown that filtration rate is a maximum, filtrate solids are at a minimum, and filter cake moisture content is at a minimum when the zeta potential equals zero. The zeta potential equals zero when 350 ppm CaO is added to a low fines content tailings stream and when 800 ppm CaO is added to an average fines content tailings stream. Testing also indicated that the amount of NaOH in the tailings stream did not have an effect on the amount of lime required. A higher amount of NaOH results in a more negative zeta potential, but it appears that the zeta potential increases to zero faster with lime addition, with no net effect of the NaOH.

Fuhr, Sanford and Lemke (1982) outline a method to optimize flocculant addition by monitoring the fines content of the tailings stream. They found that the amount of lime required is proportional to the amount of fines in the tailings stream. With 8 % < #325 sieve 200 ppm CaO was required for optimum filtration and with 18 % < #325 sieve 550 ppm CaO was required. The tailings were mixed for two minutes in a mechanical mixer at 600 rpm. It was noted that severe agitation would cause the flocs to break apart after agglomeration. The patent is for filtration and no form of deposition of the tailings is mentioned.

Roberts (1982) includes a method of depositing a sand layer on ice over a sludge layer which upon thawing will act as a permeable piston to compress the sludge layer. It mentions internal surcharging by mixing sand with sludge that has been treated with flocculants, particularly hydrolyzed starch flocculant. It also mentions total tailings mixed with flocculant, but only in terms of dyke building or as a complicated scheme involving three settlement ponds.

Yong (1983) uses hydrolyzed starch flocculants in various tailings treatment schemes. The schemes are generally complex involving two or three tailings ponds and often sand surcharge layers. He never discusses simply to mix flocculant with total tailings and deposit it in layers and allow it to settle and consolidate. This is probably because it appears that he assumes that the flocculated tailings will segregate to a degree and a "fine" tailings zone will subsequently have to be treated.

Schmidt (1987) describes using an activated carbon gel to remove the bitumen from either oil sands effluent or sludge and then flocculating the clays using a flocculating agent and allowing it to settle. The removal of the bitumen allows the flocculating agent to work more efficiently. There is no specific mention of the type of flocculating agent or of disposal schemes.

2.2.3 Summary

The most promising additives based on past work are lime and acid, combined with anionic flocculants if flocculation enhancement is required. Most of the reports do not give much in terms of geotechnical measurements and as such their usefulness is limited. Little work has been done on deposition of the tailings once agglomerated and this is an area that requires more research.

2.3 Flocculants and Coagulants In Other Industries

The use of flocculants and coagulants in other industries, although fairly common, is not reported to a large extent because often the details of the process are controlled by the chemical companies and kept confidential.. Coagulants and flocculants are used extensively in the water and sewage treatment industries, but often on quite different material from mine tailings. They are commonly used in the mine industry to flocculate tailings in-plant to prepare them for thickeners, vacuum filters, and filter presses. It is not common for them to be used to enhance settlement and consolidation in the field.

2.3.1 Water Treatment

The jar test is the standard for evaluating coagulants and flocculants in the water treatment industry. These are generally performed in one to two litre beakers and stirred with standard flat blade impellers. The intensity of mixing is expressed in terms of the mean velocity gradient which is generally calibrated to the impeller rpm and the temperature of the liquid. It is the work input into the fluid per unit of time per unit of volume and is a function of the absolute viscosity of the fluid. The coagulants or flocculants are generally added to the beakers at specific times, in specific concentrations and at specific locations in the beakers. The duration and intensity of the mixing is closely controlled, as is the pH and temperature of the mixes. The chemicals are added at a point close to the mixing blade, as it is not recommended to pour them on the water surface because thorough mixing may not be achieved. The flocculant aids are generally added to the mix immediately after the rapid mix period. After mixing, the mix is allowed to sit and the settling velocity recorded (Hudson, 1981).

The results of the jar tests are scaled up to plant requirements by scaling the mean velocity gradient and settling velocity to plant conditions. The material is generally settled and filtered in-plant and thus is generally a dissimilar operation than proposed in this thesis. The water to be treated is generally of a low solids content. The main points of interest here are the use of the flocculants and the mixing processes.

In water treatment the two major criteria governing the mixing and flocculation processes are intensity of agitation and duration of agitation. The effect of the mixing on the floc properties also depends on the type of mixing, whether it be through conduits or by various types of impellers. It has also been found that too long a mixing time has adverse effects on the floc structure (Hudson, 1981).

2.3.2 Mine Tailings

Pearse (1984) reviews the common usage of forms of acrylamide polymers to prepare tailings for vacuum filters, thickeners and filter presses. The flocculation caused by the polymers greatly increases the efficiency of the above processes. This appears to be the common use of flocculants in the mining industry, along with clarifying effluent streams with low solids contents (such as surface runoff streams). Pearse (1984) mentions the use of flocculants to prepare tailings for field sedimentation, but gives no details or examples of their actual use.

Bromwell and Oxford (1977) describe the concept of using a flocculant with a sand and clay mixture for the phosphate waste of Florida. The scheme would involve adding flocculant to a combined sand and clay mixture or flocculating the clays and then mixing with sand. The concept had not been fully proven at this point and no specific details are given on the process. It is noted though, that when flocculant is used, if the discharge is directed downward with relatively low velocity as opposed to beaching or horizontal pipe discharge, segregation is minimized.

2.4 Clay Aggregation by Flocculants and Coagulants

Traditionally, coagulants have been designated as agents that cause aggregation of colloids by changing their surface characteristics or surface charge. Generally, this is achieved by changing the solution electrolyte strength. Flocculants have been designated as those chemical agents that cause chemical bonding of colloids (Sato and Ruch, 1980). In these terms, calcium ions are coagulants and polymers such as Cyanamid A-110 (used for this project) are flocculants. Sulphuric acid is hard to fit into these categories as it causes flocculation due to a pH change. For the remainder of this thesis, flocculation will be used for both the coagulation and flocculation processes except when referring to the work of others.

Electrolytes cause flocculation of clay particles by lowering their surface charge, thus reducing the repulsive forces and allowing attractive forces to bond the particles together. Clay particles have a net negative charge due to missing silica and aluminum ions in the clay particle crystal lattice. Ions such as Ca^{2+} reduce this charge by substituting for the missing ions in the crystal lattice (often replacing Na^+ in a process called ion exchange). Attractive forces, mainly van der Waals forces, then cause the particles to agglomerate.

Clay preferentially adsorbs multivalent ions, thus small amounts of these added to a clay-water-monovalent system can cause flocculation. The sources of cation exchange are isomorphous substitution, broken bonds at the particle edges and replacement of the hydrogen of an exposed hydroxyl. The first is the major cause for most clays except for kaolinite, where broken bonds play a major role. The exchange reaction in kaolinite is almost instantaneous, resulting in quick flocculation after electrolyte change. The exchange reaction is much slower for illites and montmorillonites (Mitchell, 1976).

As mentioned earlier, the addition of a mineral acid such as sulphuric acid causes flocculation due to a pH change. There are two factors controlling the effect of pH change on clays. The first is that clay particles have hydroxyl (OH) exposed on their surface and edges and the tendency for the hydroxyl to dissociate by the equation:

$$SiOH \longrightarrow SiO^- + H^+$$

is strongly influenced by the pH. The higher the pH, the greater the tendency for the H^+ to go into solution and the greater the effective negative charge on the particle. The second factor is that the alumina which is exposed on the edge of particles is amphoteric and ionizes positively at low pH and negatively at high pH. The result of both factors is that at high pH, the particle repulsion is increased and the clay is more stable and at low pH, the repulsion is decreased and positive edge to negative surface attraction causes flocculation. This role of pH is much larger for kaolinite, lesser for illite and relatively unimportant in montmorillonite (Mitchell, 1976).

Flocculation by polymers is generally attributed to two processes. The first is charge neutralization by polymers of opposite sign to the particles. The other is by particle bridging by high molecular weight polymers of neutral or the same sign as the particles. Charge neutralizing polymers appear to work by adsorbing onto the surface of the particles due to electrostatic attraction. This results in a lowering of the repulsion between clay particles (Sato and Ruch, 1980).

Bridging of particles by polymers may occur for two reasons. The first is by bridging of two or more particles on one polymer chain. The second is by the interaction of polymer chains that have one or more particles adsorbed onto them. The first occurs at low polymer concentrations where the chain is long enough to adsorb onto two or more particles. The second occurs when the polymer chains are very long and the polymer concentration is close to saturation values. These saturation values can be quite small and if the concentration is increased beyond these values the colloids will begin to disperse due to repulsion of the polymer chains.

A high molecular weight polymer of the same sign as the colloids works as a flocculant aid after the tailings have been treated with cations such as Ca^{2+}. The cations are used for charge neutralization which allows the clay particles to come close enough together for flocculation by bridging due to the polymer (Sato and Ruch, 1980). Flocculant aids are generally low to medium charged, high molecular weight (in the order of $1x10^6$) polymers.

The charge of the polymers is dependent on the degree of hydrolysis, with the higher degree of hydrolysis, the higher the charge. A higher charge results in a fluid with higher viscosity. The molecular chains become more stretched with a higher charge due to repulsion of hydrolyzed ions. Cyanamid A-110, used in this study, is a medium charged polymer with 10-20 % hydrolysis which gives randomly kinked or flexing coils (Bratby, 1980).

2.5 Mixing

Some aspects of mixing are reviewed here to help understand mixing in the laboratory and also as a starting point for understanding how to scale up to the field from laboratory data.

When mixing in a vessel, the variables which affect the uniformity of solids suspension are: vessel geometry, impeller construction, operating speed, particle density, solids concentration, density of liquid phase, size range and shape of particles, viscosity of fluid phase and hindered settling (mixes which undergo hindered settling will have a slurry viscosity) (Lyons, 1967). Hindered settling slurries are non-Newtonian, that is the viscosity is dependent on the magnitude of the shear stress or shear rate. As the viscosity of the mixture goes up, the smaller is the zone of mixing and thus either the size of the mixing container has to decrease or the speed of the impeller has to increase. Circulation in a vessel is one of two types: upwards flow which lifts the slurry or universally directed which distributes the solids into the fluid.

It is noted that the best method to mix suspensions such as sand in water (tailings before flocculation) are bottom mounted flat blade turbines, with either stator blades or side mounted baffles to ensure uniform mixing. This ensures horizontal flow along the bottom of the vessel to scour the sand and that the maximum vertical velocity is at the bottom of the vessel where it is required to lift the sand. Propellers are more effective where the apparent viscosity of the slurry impairs settling of the solids, such as occurs after flocculation (Lyons, 1967). At the laboratory scale, either type of impeller would work fine, but for a larger scale, a propeller would be preferred, as less energy would be required to keep the tailings mixing. It is recommended that at least a four inch diameter impeller be used for bench tests to scale up to field tests, as scale effects are too large for any smaller impellers.

It is also noted that a curved blade turbine blade is thought to reduce the shear of mixing, an important aspect in flocculated mixtures. Also, the determination of agitator power is quite involved. It is dependent on the following variables: impeller diameter, tank diameter, liquid depth, clearance of impeller off tank bottom, blade width, pitch of blades, number of blades, blade length, fluid density, fluid viscosity, power, impeller rotational speed, gravitational acceleration and Newton's law conversion factor. In non-Newtonian fluids, such as flocculated tailings, the viscosity changes with shear, making the calculations more complex. There are correlation charts available for specific impellers based on the above variables. (Bates et al, 1967).

2.6 Hindered Settling and Consolidation

2.6.1 Introduction

To model the sedimentation and consolidation of a material, laboratory testing is first conducted to determine the settlement characteristics (interface height with time), compressibility (void ratio with stress) and hydraulic conductivity with change in void ratio. These values are then used with an appropriate theory to predict sedimentation and consolidation in the field.

2.6.2 Hindered Settling

2.6.2.1 Hindered Settling Testing

Hindered settling is generally modelled in standpipes, with the most basic measurement being the rate of fall of the interface between the solids and supernatant water with time. Auxiliary measurements include pore pressure measurements at ports along the side of the standpipe and measurement of the density of the slurry at selected time intervals using either x-ray or gamma-ray techniques.

The pore pressures were measured for some tests performed here, but most were of standpipes with no instrumentation. Density profiles were not measured as the time and expense were not justified. Sufficient information was obtained from the standpipes alone.

The most important information was whether the sample segregated, the settlement characteristics of the mix and the final properties of the tailings. Density profiles with intermediate time were not considered to be of great importance.

2.6.2.2 Hindered Settling Theory

Sedimentation consists of two phases, a particulate settling phase where particles fall individually according to Stokes Law and a hindered settling phase where particles interact and settle en-masse. After hindered settling, effective stresses will begin to develop between particles and the soil will settle at a much slower rate, governed by hydrodynamic consolidation (Tan et al, 1990; Been and Sills, 1981; McRoberts and Nixon, 1976). At the tailings concentrations used in this study, particulate settling will not occur and will not be discussed further.

Hindered settling theory was first developed by Kynch (1952) for batch settling analysis. The theory is based on the assumption that the velocity of settling is a function of local concentration only. The original theory was based on particles of equal size. McRoberts and Nixon (1976) extended this to include non-segregating soils and define the concentration, c, as the mass of particles per unit volume as opposed to the number of particles per unit volume as defined by Kynch (1952). The velocity of settling was also re-defined relative to a point rather than a particle.

The concentration is defined as: $c = G_s(1 - n)\gamma_w$, where n = porosity. The particle flux is then defined as the weight of particles crossing a horizontal section per unit time, or: S = vc. The governing equation for hindered settling is then derived as:

$$\frac{\partial c}{\partial t} + V(C)\frac{\partial c}{\partial x} = 0 \qquad 1)$$

where: V(c) = -ds/dc

The hydraulic conductivity can be determined from the interface settlement curve for a hindered settling material using the method of Tan et al (1988). The equation, as developed by Been (1980), is:

$$k = \frac{v_s G_s \gamma_w}{c(\frac{\gamma_s}{\gamma_w} - 1)} \qquad 2)$$

The concentration and velocity of interface fall is determined by Kynch's graphical procedure and the method ignores any consolidation that occurs during the hindered settling phase. The work of Tan et al (1988) shows that the permeability - void ratio relationship is not unique for an active soil, but depends on the initial void ratio.

A slurry such as the one studied here goes through three zones of settling based on the shape of the interface settlement curve. These are; a constant rate period, where hindered settling dominates and the void ratio of the soil in the hindered settling zone remains at the initial void ratio; a first falling rate period, where effective stresses start to develop and hindered settling and self-weight consolidation both affect the settlement; and a second falling rate zone where consolidation dominates. It is in the middle transition zone where the void ratio changes from the initial void ratio to the void ratio at which consolidation proceeds. This zone is incorporated into a combined theory of hindered settling and non-linear finite strain consolidation by Pane and Schiffman (1985) and Schiffman et al (1988), as discussed in section 2.6.3.2.

Laboratory testing of sediment columns to measure the density of solids using x-ray or gamma-ray techniques or by careful sampling have shown that the hindered settling zone will often show a void ratio above the initial void ratio due to water being squeezed out from below (Been and Sills, 1981; Imai, 1981; Tan et al, 1990). It is possible that this phenomenon could also be due to partial segregation of the samples, resulting in more fines in the hindered settling zone, and thus a higher water content. This appears to be at least partially to blame in the work of Been and Sills (1981) and Imai (1981) where the samples that segregated definitely showed this trend. It appears to be sufficient to assume that the void ratio remains at the initial void ratio during the hindered settling stage. These studies have also shown, at least for the clay samples tested, that the transition zone is quite thin, with a rapid decrease in void ratio across it.

2.6.3 Consolidation

2.6.3.1 Consolidation Testing

The traditional method of measuring consolidation of a soil is the oedometer. This method was first proposed by Terzaghi (1924). It is performed by applying step loads to a thin sample and monitoring deformation with time. The void ratio - effective stress relationship is determined directly and the coefficient of consolidation is calculated using an inversion of any of several consolidation relationships. The main disadvantage of the test, as outlined by Znidarcic et al (1984) is the duration of the test, which for some materials can take months. The standard oedometer is also not designed to easily accommodate the initial fluid behaviour and large strain involved with testing slurries.

For this reason, large diameter slurry consolidation cells have been developed (Bromwell and Carrier, 1979: Scott, Dusseault and Carrier, 1986). The test is performed in the same manner as the oedometer test with loads added in increments to the sample. The duration of each load step is much longer than the standard oedometer test due to an increased sample thickness and since single drainage is used (to more closely model field conditions). Pore pressures are also monitored, as generally pore pressures do not dissipate at the same rate as deformations (Schiffman et al, 1988). The main disadvantage with this test procedure is the great length of time required to perform a test.

Several testing methods have been proposed to speed up consolidation testing. These include the constant rate of deformation test, controlled gradient test, constant rate of loading test, continuous loading test, seepage test and relaxation test. These are summarized in Znidarcic et al (1984). These tests are considerably faster than the step load test. The main disadvantage is the interpretation of the results which relies on an inversion of a consolidation theory to obtain the void ratio - effective stress relationship (except for the seepage test). The inversion theory generally requires restrictive assumptions which do not work well for materials which undergo large deformations. Another problem is that permeability cannot be directly measured and has to be back calculated from the results.

Theories for the analysis of constant rate of deformation tests have been proposed by Smith and Wahls (1969), Wissa et al (1971), Umehara and Zen (1980), Lee (1981) and Znidarcic et al (1986). Smith and Wahls (1969) use a simplified finite strain theory. The main limiting assumption is that the void ratio is a linear function of the time and space variables. A parameter b is used, which is unknown and has to be determined by comparison to reference tests. The method also does not appear to work for ratios of the pore pressure at the base to the total stress above 0.5.

Wissa et al (1971) use an inversion of an infinitesimal theory in which the self-weight of the material is neglected and the coefficient of consolidation is assumed constant. The analysis has two forms, a linear and a non-linear model. Additional assumptions are that the coefficient of volume change for the linear model and the compression index for the non-linear model are constant. The consolidation process is divided into two phases, an initial transient phase followed by a steady state phase. The length of the transient state depends on the rate of loading and upon the magnitude of any initial load on the sample. The procedure for calculating the stress-strain behaviour for the transient portion is complex and relies on an assumption of the ratio of the strain at the top and bottom of the sample.

The analysis of Umehara and Zen (1980) is based on an inversion of a finite strain theory. The simplifying assumptions here are that the coefficient of consolidation and compression index are assumed constant and that the sample has an initial uniform void ratio. The ratio of strains is determined in the same manner as the method of Wissa et al (1971) and then charts are used to determine the void ratio effective stress relationships at each end of the sample.

The method of Lee (1981) is the same as that of Wissa et al for the transient portion of the test. The steady state portion of the analysis is updated to a finite strain formulation by continuously updating the height of the sample during the analysis. This is made simpler by assuming that the strain distribution within the sample can be approximated by a parabolic function, as given by infinitesimal strain theory. The procedure requires the use of a numerical method such as a finite difference program to handle the calculations.

Znidarcic et al (1986) propose a method that does not include most of the simplifying assumptions of the previous methods. The largest assumption is that the self-weight of the sample is ignored. The analysis is based on the non-linear finite strain theory as proposed by Gibson et al, (1967). It is the most complex of the methods and involves an iterative procedure that is solved using a finite difference program.

The methods of Smith and Wahls, Wissa et al and Umehara and Zen were chosen here due to their simplicity and are compared in section 4.

2.6.3.2 Consolidation Theory

The classical theory of consolidation and the one still used for most analyses is the theory developed by Terzaghi (1924) and given by the equation:

$$\frac{\partial u}{\partial t} = C_v \frac{\partial^2 u}{\partial x^2} \qquad 3)$$

where u is the excess pore pressure and c_v is the coefficient of consolidation defined by:

$$C_v = \frac{k(1 + e_o)}{a_v \gamma_w} \qquad 4)$$

where k is the permeability, e_o is the initial void ratio, and a_v is the coefficient of compressibility.

The assumptions incorporated in the theory include a linear stress-strain (compressibility) relationship, a constant permeability and infinitesimal strain. There have been several extensions to the original theory to account for non-linearity in the stress-strain or permeability-void ratio relations and these have been reviewed in the paper by Olson and Ladd (1979). None of these theories are strictly applicable to the tailings tested here due to the large strains that occur when slurries are consolidated. A finite strain theory is required.

The simplest finite strain theories are ones that use an infinitesimal strain theory in a finite difference program (Olson and Ladd, 1979; Yong et al, 1983). The soil parameters are adjusted such that the method is linear between time steps, but non-linear with finite strains with continuing iterations. Due to its ease of programming, the method of Yong et al (1983) is used here to analyse the self-weight consolidation of the tailings as tested in standpipes, with input from consolidation and permeability tests. The program allows hindered settling to occur at the top of the sample while consolidation builds up from the bottom. It is assumed that the tailings settle at the initial void ratio until they reach the consolidation front, where they collapse to the void ratio where consolidation begins. The void ratio at the beginning of consolidation is not a constant and will depend on the amount of flocculation and coagulation of the clays and the initial void ratio of the sample. It is determined by examination of the settlement curve and trial and error.

The void ratio-permeability and void ratio-effective stress relationships determined from the standpipe, slurry consolidation and permeability tests are input into the program as power laws of the form: $e = A\sigma'^{B}$, $k = Ce^{D}$. This was adopted for compatibility with the method of Somogyi (1980), as used in the program developed by Pollock (1988). The program by Pollock is used to predict the accumulation of tailings in-pit once the material parameters have been confirmed in the previous program. The upper boundary is treated as a moving boundary as tailings are incrementally added to the pit, with the initial void ratio the void ratio at the beginning of consolidation.

There are several finite strain consolidation methods which include the self-weight of the soil and none of the restrictive assumptions of the original theory. These are reviewed in Pollock (1988). These methods are generally based on either the finite strain theory of Mikasa (1965) or Gibson et al (1967). The latter theory has found more use in practice, likely since it places no restrictions on the initial void ratio condition. The governing equation for the theory of Gibson et al in one-dimensional form is:

$$\pm\left(\frac{\gamma_s}{\gamma_f} - 1\right)\frac{d}{de}\left[\frac{k}{1+e}\right]\frac{\partial e}{\partial z} + \frac{\partial}{\partial z}\left[\frac{k}{1+e}\,\frac{d\sigma'}{de}\,\frac{\partial e}{\partial z}\right] + \frac{\partial e}{\partial t} = 0 \qquad 5)$$

The method of Somogyi (1980), used here in the program by Pollock (1988), reformulates the governing equation of Gibson et al (1967) in terms of excess pore pressures and solves it using a fully implicit central finite difference method. The governing equation in terms of finite differences becomes:

$$
\begin{aligned}
&S_{i,j}\delta(K_{i,j} + D_{i,j})u_{i+1,j+1} + (1 - 2S_{i,j}k_{i,j}\delta)u_{i,j+1} \\
&+S_{i,j}\delta(K_{i,j} - D_{i,j})u_{i-1,j+1} = u_{i,j} + \gamma_b\Delta z \\
&S_{i,j} = \sigma'_{i,j}{}^{\beta} / AB\gamma_f ;\ K_{i,j} = k_{i,j} / (1 + e_{i,j}) \qquad 6) \\
&D_{i,j} = 1 / 4((k_{i+1,j} / (1 + e_{i+1,j})) - (k_{i-1,j} / (1 + e_{i-1,j}))) \\
&\delta = \Delta t / (\Delta z)^2
\end{aligned}
$$

Pane and Schiffman (1985) and Schiffman et al (1988) present a theory which combines hindered settling and finite strain consolidation. This would be very useful here, but due to time constraints its application is left to future analyses.

2.6.4 Permeability Testing and Theory

Permeability or more appropriately hydraulic conductivity values may be determined in the laboratory using either indirect or direct methods. Hydraulic conductivity can be determined using indirect methods by inverting a consolidation theory and using it to interpret the results of a consolidation test. Direct methods involve forcing a permeant through a soil and recording the rate of flow or the associated hydraulic head changes.

Indirect methods of determining hydraulic conductivity have been found to often result in considerable error when compared with measured values. Olson and Daniel (1981) report a range of the ratio of measured to back calculated hydraulic conductivities of 0.9 to 5.0. Tavenas et al

(1983) report that back calculated values underestimated the measured values by up to six times. They observe that for step loading tests interpreted using Terzaghi's theory that the difference is likely due to the incorrect assumptions that the compressibility, permeability and coefficient of consolidation remain constant during the test, especially for soft soils. They also show that the hydraulic conductivity determined from constant rate of strain tests are particularly inaccurate due to several reasons: 1) most interpretation theories include restrictive assumptions, as discussed above, 2) a non-uniform void ratio generally occurs during a constant rate of strain test, especially at the drainage boundary and 3) large gradients occur through the sample, due to the high pore pressures at the base of the cell.

The direct methods of determining hydraulic conductivity in the laboratory are the constant head and falling head tests. These may be performed in triaxial cells, oedometer cells or in specially built permeameter cells. The tests are generally quite simple to setup and interpret but require a long testing period if low gradients are to be used for low hydraulic conductivity materials (Olson and Daniel, 1980). Pane et al (1983) show that large gradients, common in many permeability tests, will cause consolidation. It is practically very difficult to perform falling head tests at low gradients. This leaves the constant head test at low gradients to test underconsolidated materials.

One concern with hydraulic conductivity testing is whether flow obeys Darcy's law, as the interpretation theories generally assume. It appears from the work of Tavenas et al (1983) and Olsen, Nichols and Rice (1985) that as long as small gradients are used, a linear flow-gradient relationship should be expected.

Another consideration in permeability testing is the phenomenon of decreasing flow rates at the beginning of a test, especially for low gradient tests (Olsen, Nichols and Rice, 1985). With time, the flow reaches a steady state level which then obeys Darcy's Law. This transient condition is likely due to time dependent changes within the sample and is more dominant in finer grained soils. Pollock (1988) shows that for an 80 % sand - 20 % fines oil sand tailings mixture that the transient portion exists but occurs for a shorter time period and is much smaller than for higher fines content mixtures.

Hydraulic conductivity is calculated from laboratory data of flow rate and the area of the permeameter using the following equation:

$$k = \Delta V / \Delta t A i \qquad 7)$$

where, i = hydraulic gradient = $\Delta h / H$

3. Testing Program

3.1 Summary of Testing Program

The testing program is centred around determining the depositional characteristics of non-segregating mixes of total tailings. It consists of standpipe sedimentation tests, slurry consolidation tests, and associated geotechnical index tests. The tests were performed on total tailings supplied by Syncrude Canada Ltd. Non-segregating mixes were achieved using either lime (CaO), sulphuric acid (H_2SO_4) or lime and a chemical flocculant (Cyanamid A-110).

This chapter is divided into three main sections. The laboratory equipment is first described, followed by the tailings preparation and laboratory procedure and then the properties of the tailings used for the test program are described.

3.2 Equipment

3.2.1 Standpipe Tests

Standpipes of four different sizes were used. The smallest of these were 1 litre hydrometer cylinders. These are small glass cylinders averaging 36 cm in height and 6 cm in diameter. These were the only clear cylinders, where the sediment could be observed through the side of the cylinder. A limited number of tests were performed in these cylinders, as it was uncertain whether their small diameter would affect the sedimentation and consolidation processes.

The stainless steel cylinders used for the consolidation tests, described in section 3.2.2, were also used for a limited number of sedimentation tests. These are two cylinders 17.14 cm in diameter and 37.5 cm in height, with a volume of 8.6 litres. The hindered sedimentation and self-weight consolidation portions of the consolidation tests are also included with the standpipe test results.

The majority of standpipe tests were performed in 30.5 cm diameter PVC cylinders 60 cm in height, with a total volume of 44 litres. PVC was chosen because of its relatively low cost and high durability, enabling the tailings to be mixed inside the cylinders. Cellophane wrap placed over the top of the standpipes was used to reduce the evaporation of the decant. These were not instrumented and were used to determine the tailings-decant water interface with time as settlement and consolidation occurred.

Also, two 2 m high standpipes of the same size PVC were used. The total volume of these was 146 litres or approximately 4/5ths of a 45 Imperial gallon barrel. These were instrumented with manometers to better analyse the stages of settling and consolidation of the mix (Fig. 3.1). Ten manometer ports were positioned every 20 cm up the cylinder. The details of the manometer ports are shown in Figure 3.2. The standpipes were also mounted on pallets, so they could be moved through the laboratory to place or remove tailings and to ensure that they would not fall over.

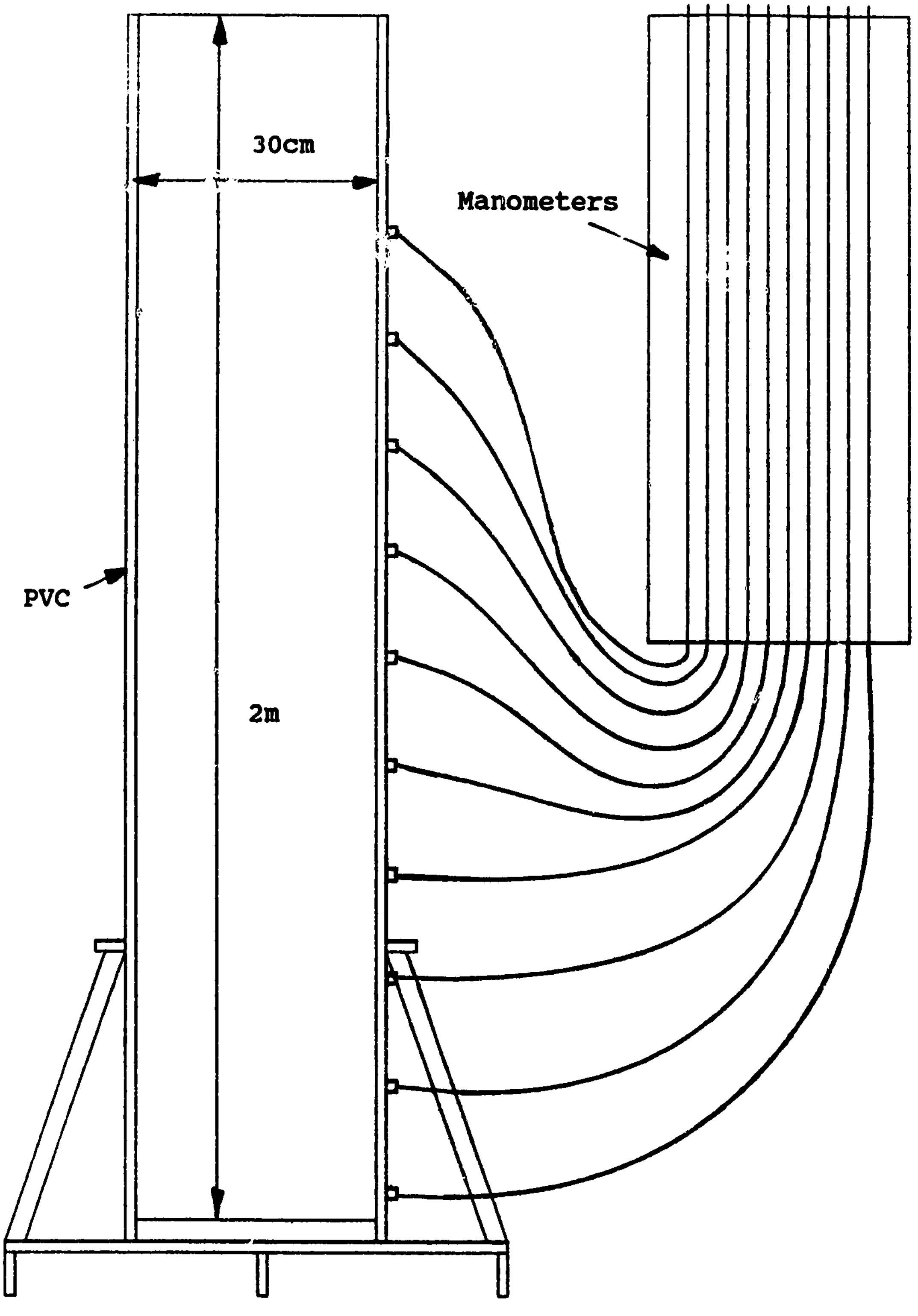


Figure 3.1 Two Metre Standpipe

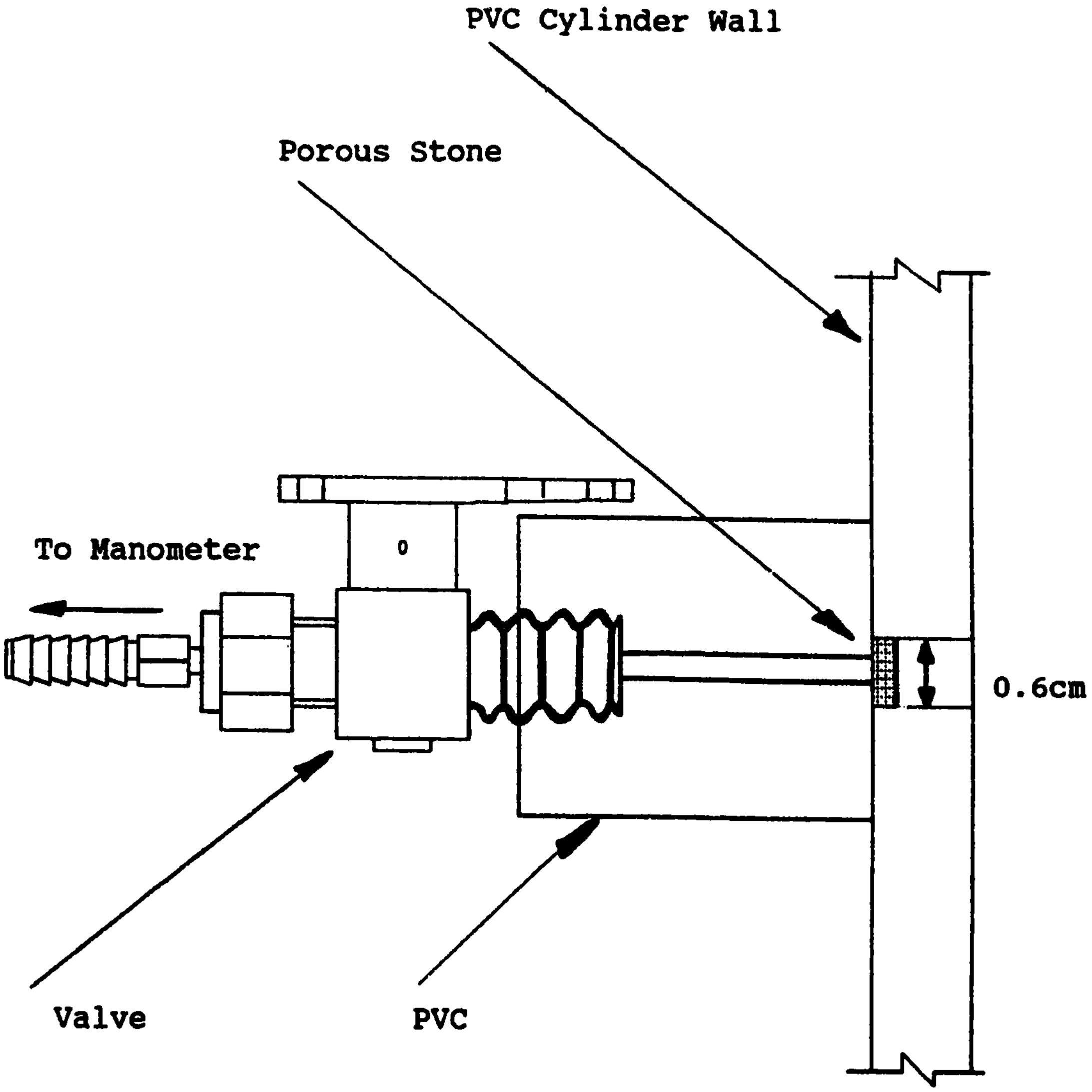


Figure 3.2 Valve Assembly for Two Metre Standpipes

One tall standpipe was also equipped with a loading piston as illustrated in Figure 3.3. This was used to load the sample after self-weight consolidation was complete. The piston was made of PVC, with four stainless steel rods to prevent the piston from tipping. Wellman Quline Q-140 geotextile was used as a filter beneath the piston. The piston was found to have no measurable friction on the cylinder walls. The weight of the assembly, 6.77 kg, was used as the first load. Following this, lead shot was used to load the piston.

3.2.2 Consolidation Tests

Two types of slurry consolidation tests were performed and compared. These were step-loading and constant rate of deformation tests. Both types of tests employed single drainage through the top piston. The step loading tests required about two months to complete while the constant rate of deformation tests required about 5 to 10 days.

3.2.2.1 Step Loading Consolidation Apparatus

The step loading tests were performed in stainless steel cylinders 17.14 cm in diameter and 37.5 cm in height (Fig. 3.4). The pore pressure was measured at the base of the cylinder beneath a porous plate, with a Validyne pressure transducer having a 35 kPa maximum pressure. The travel of the piston was measured using a 15 cm travel linear variable displacement transducer (LVDT). The load was

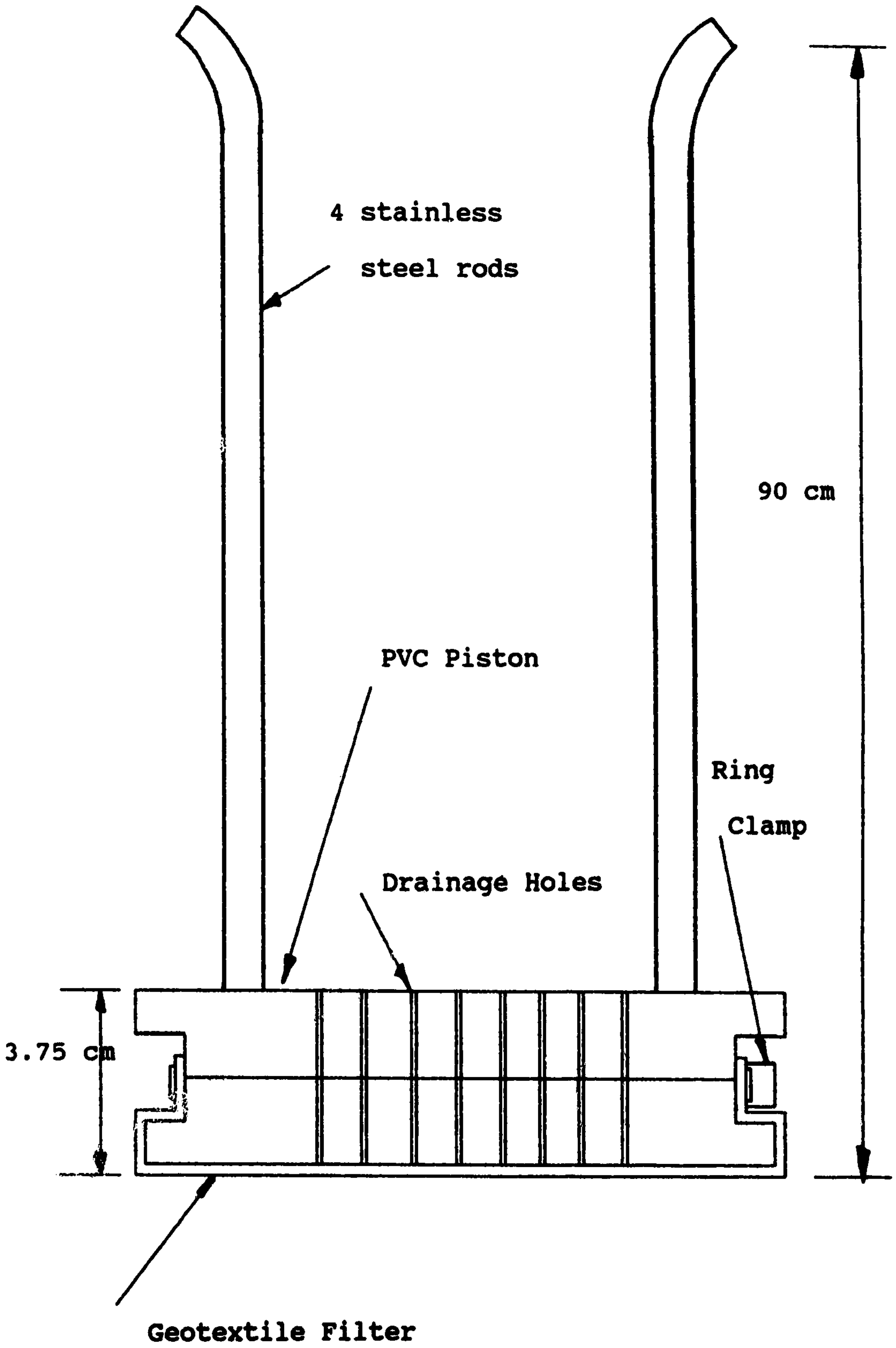


Figure 3.3 Piston Assembly for Two Metre Standpipes

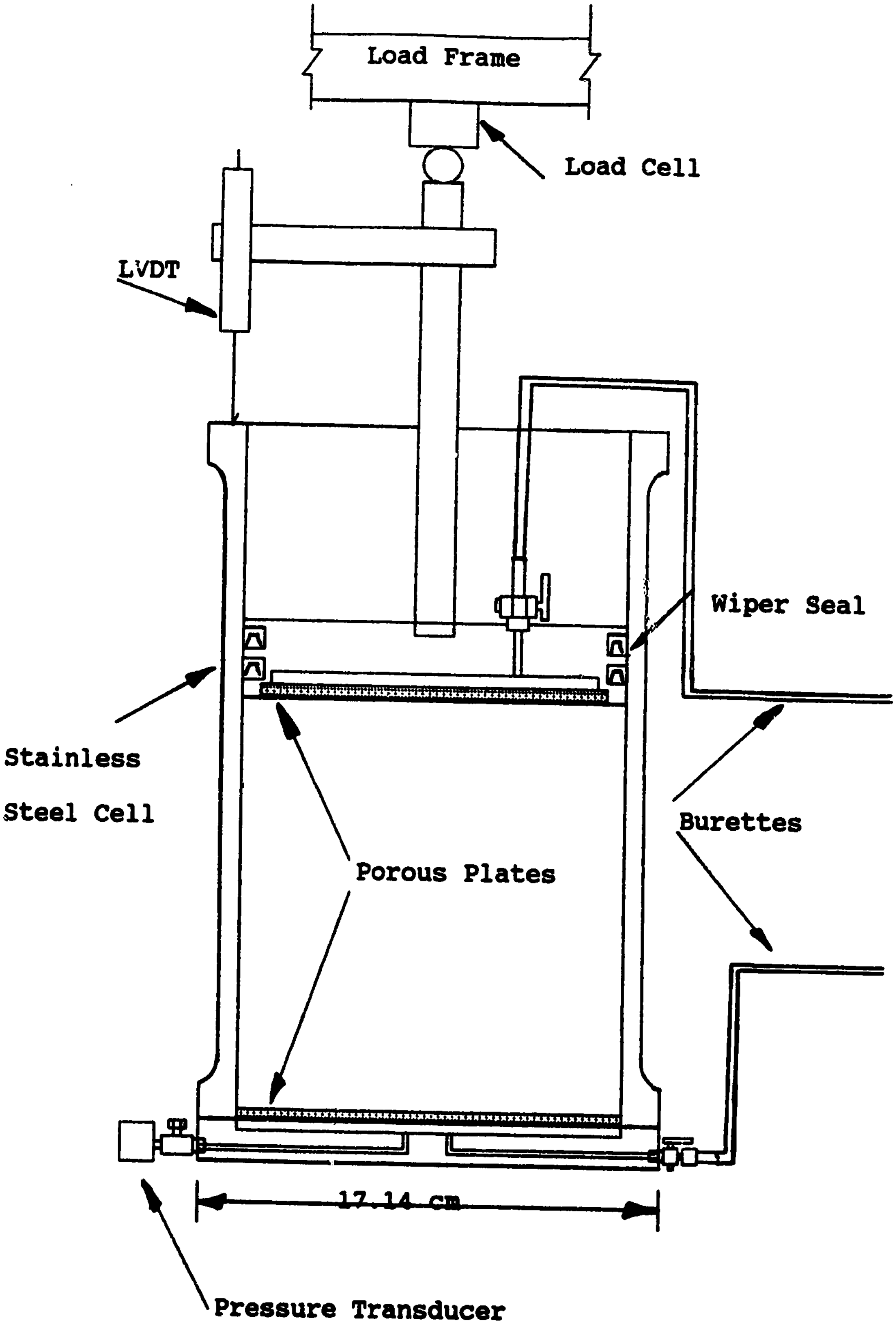


Figure 3.4 Step Load Consolidation Cell

applied using dead weights for the smaller loads, up to 10 kPa, and a diaphragm air cylinder for the larger loads. The loads applied by the air cylinder were measured using a load cell in the piston rod and were regulated using a pressure regulator and gauge. The cell was placed in a loading frame, with the air cylinder bolted to the top. The load cell was fabricated at the University, and had a maximum rating of 600 kg. The measurements were recorded at a pre-set time on a Fluke datalogger in the laboratory. The calibrations and details of the sensors can be found in Appendix A.

The piston was sealed using two Parker U-Packing wiper seals. These provide a good seal with relatively low friction. The piston was prevented from tipping, and thus developing any excess friction, through the use of a top cap with a bushing through the centre for the loading rod. The bushing exerted no measurable friction on the loading rod. The drainage was through a porous plate in the piston, through a valve and then through a hose connected to a horizontal burette positioned two cm above the top of the sample. This provided a small amount of constant back pressure on the system. The position of the burette was adjustable to enable it to be moved as the piston moved.

The cell was also set up to perform permeability measurements between loading stages. A constant head permeability test was chosen, so that any decrease in flow rate with time could be monitored and the steady state permeability determined (Pollock, 1988). This would not be possible with a falling head type of test. The constant head was achieved using two burettes positioned horizontally on a burette stand. The top burette was connected to the bottom of the cell, beneath a porous plate and the bottom burette was connected to the hose used for drainage for the consolidation portion of the test. Upward flow was used to ensure that no consolidation of the sample occurred during permeability testing. A clamp attached to the loading frame and piston rod was also used to ensure that the piston did not move during the permeability stage. The drawback of this setup was that only small gradients could be achieved, as the gradients were limited by the height that the manometers could be raised.

3.2.2.2 Constant Rate of Deformation Consolidation Apparatus

Two different sets of equipment were used for the constant rate of deformation tests. The first cell used for these tests is shown in Figure 3.5. The cylinder portion of the cell was made from the same size PVC as the standpipes described in section 4.2.1. Four pressure transducers were connected to ports along the side of the cell. The bottom port was beneath a porous stone at the base of the cell. The total stress was measured at the base of the piston using an earth pressure cell. An LVDT connected to the piston rod was used to measure travel. The cell was placed

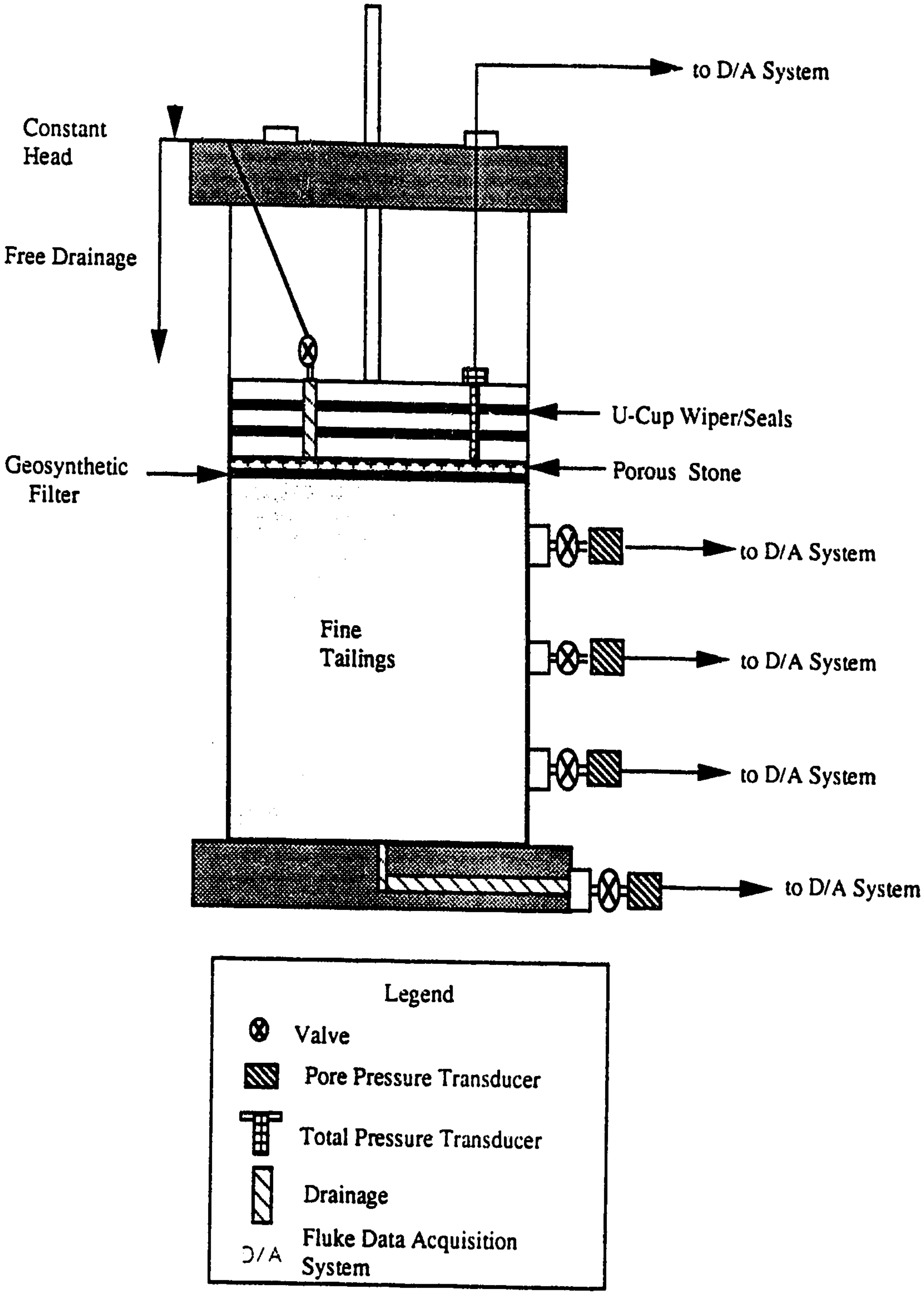


Figure 3.5 Constant Rate of Deformation Consolidation Cell

in a load frame and the constant rate of deformation loading was provided by an air cylinder in a loading frame sending hydraulic oil at a constant rate to a second air cylinder on top of the loading frame. The equipment was set up in a coldroom maintained at 2 degrees Celsius. The data was recorded at pre-set times on a Fluke datalogger in the laboratory. The details and calibrations of the sensors are in Appendix A.

After four tests were attempted with this setup, it was abandoned due to problems with water leaking past the piston. A combination of low friction with an effective seal was not found for this setup, possibly due to scoring of the PVC by the sand grains in the tailings.

The replacement cell used for the final constant rate of deformation tests was identical to the cell used for the step loading tests, except that the permeability portion was not included and the top drainage was allowed to drain into a graduated cylinder (Fig. 3.6). It was found that air in the system, either from leaks in the drainage line or gas or air escaping from the sample made it too difficult to drain into a burette. Thus the hydrostatic pressure on the sample was to the top of the cylinder, where the water level in the drainage hose remained during the test.

The constant rate of deformation was achieved by placing the cell in a Tritest 50 (Engineering Laboratory Equipment Ltd.) loading frame. The load was measured using a 900 kg load cell between the piston rod and the top of the

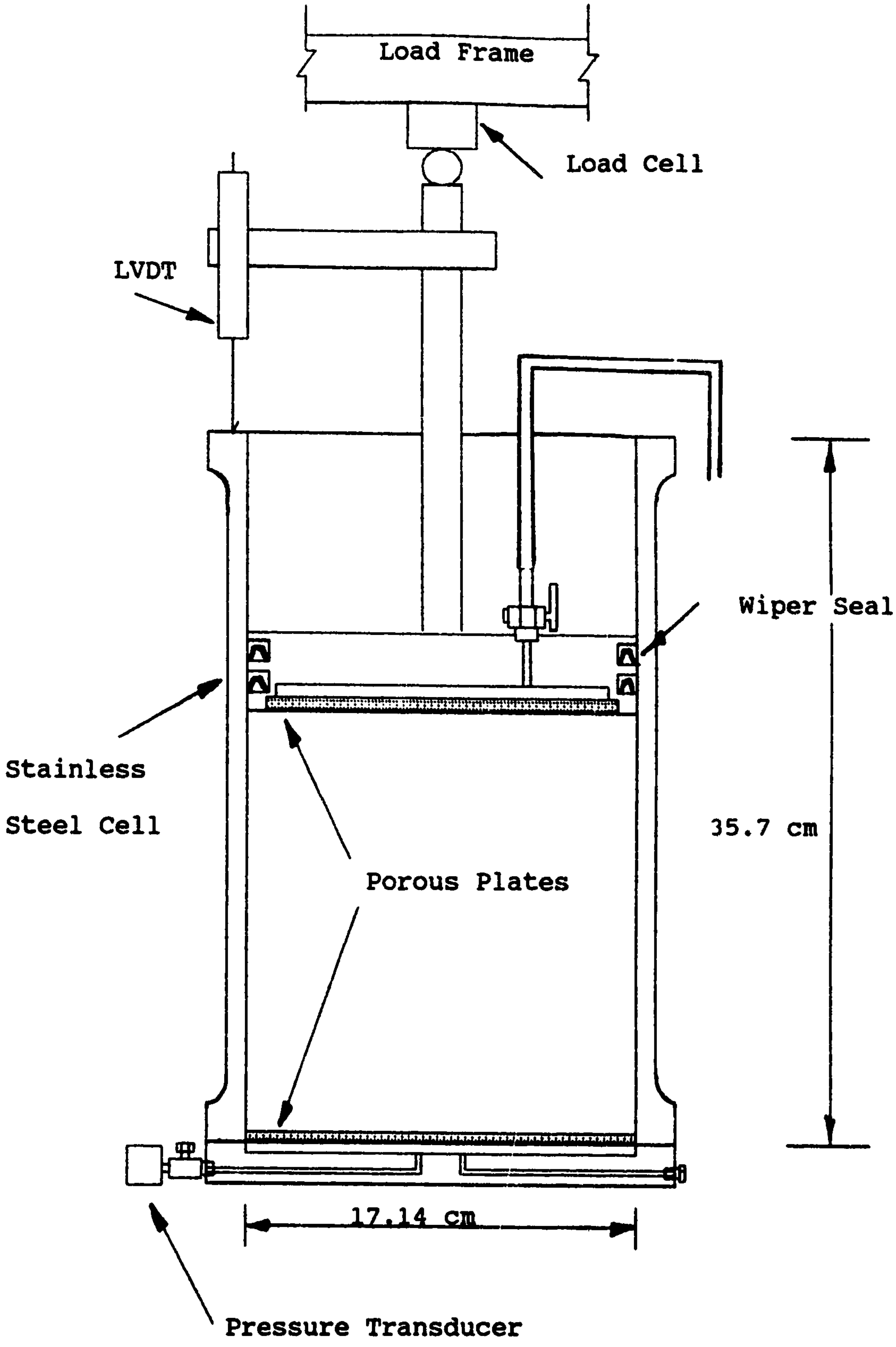


Figure 3.6 Constant Rate of Deformation Consolidation Cell

frame. The deformation was measured with a 15 cm travel LVDT and the pore pressure at the base of the cell with a 35 kPa Validyne pressure transducer (see Appendix A for details). The information was recorded on a datalogger in the laboratory once every two hours.

3.3 Procedure

3.3.1 Tailings and Flocculant Preparation

The tailings were prepared for testing in the shorter PVC standpipes by dividing a barrel of tailings into five portions. This resulted in five standpipes 40 to 55 cm in height. The barrel was divided equally by removing thin layers and dividing into five portions by weight. The fine tails zone at the top of the barrel was siphoned off and mixed before dividing. The sand at the bottom of the barrel was well compacted by the vibration of travel and had to be removed using a shovel. The results will show that the dividing process was generally adequate in obtaining mixes with similar average void ratios. The tailings used for the consolidation tests were first prepared and mixed in the PVC standpipes and then poured into the consolidation cells.

The tailings were mixed in the standpipes using a blade mixer on a variable speed drill (Fig. 3.7). (This type of mixing blade has a small area of contact with the mixture and requires high velocities to mix and thus is a high shear type of mixer). This impeller was used as it was able to stir the sand at the bottom of the barrel into suspension

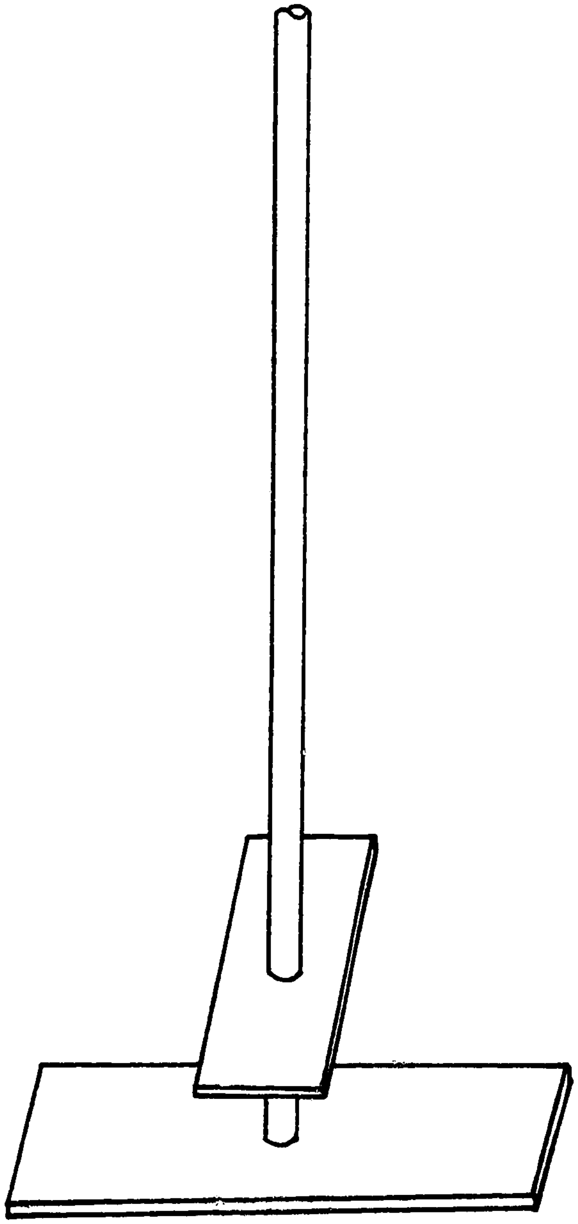


Figure 3.7 Blade Mixer

without undue load on the drill. A conventional blade impeller would be more efficient for mixing, but would be very hard on the drill while getting the sand in suspension. The tailings were mixed for five minutes to get the sand in suspension before adding the flocculant.

The 1 litre samples were prepared on a volume basis by adding 55 % sand and 45 % fine tails to a cylinder and verifying the average void ratio using the weight and volume of tailings. A void ratio range of 0.1 was obtained between all tests. This method likely results in some variation in grain size between tests, but was adequate here since these were only preliminary tests and all samples came from the same pail of tailings. The tailings were mixed at first with a 4 litre soil mixer, but this was found to add a considerable amount of air to the sample. The final 1 litre tests were mixed with a vane shear blade on a variable speed drill. This was found to add less air, but since the samples were so small it was difficult not to entrain some air, as the blade had to be turned very slowly.

The tailings for the 1.9 m standpipes were mixed directly in the barrel using a 15 cm diameter ice auger. It was decided that this would be the easiest method of mixing a whole barrel at once. This was required as the tall standpipes hold four-fifths of a barrel. The ice auger was found to be an excellent method of mixing tailings, as the tailings appeared to flocculate immediately when the flocculant was added and it did not appear to add air to the mix. The drawbacks are that it requires at least two people and a fair amount of physical exertion to get the sand in suspension and then hold the auger up while the tailings are mixing.

This was also the method used to mix the tailings in the barrels to take samples for the initial tailings properties. The tailings were completely mixed, with all sand in suspension, and then three samples were scooped from the centre of each barrel while mixing continued. The properties of the tailings are presented in section 3.4, where the tailings are described.

The lime and polymer were added to the tailings in proportions based on the dry weight of the quick lime (CaO) or polymer as a fraction of the total weight of the tailings. The sulphuric acid was added in proportions based on the volume of acid in ml as a fraction of the total volume of tailings in litres. Although this is not necessarily the best way to judge how much flocculant to use, this has generally been the convention in the earlier work done. A method of proportioning the amount of flocculant based on the proportion of solids or clays in the sample or the zeta potential of the tailings would likely give more consistent results.

The lime was prepared for adding to the tailings by slaking the dry quicklime in distilled water. The quick lime reacts with the distilled water to form hydrated lime by the following equation:

$$CaO + H_2O \quad <--> \quad Ca(OH_2) + heat$$

The lime is hydrated before addition to the tailings as it ionizes more readily in water into Ca^{2+} and OH^- ions (Boynton, 1980). The calcium ions are what cause the clays to flocculate as described in section 2.4. Distilled water is used here so that any unwanted ions from Edmonton tap water are not included. The quality of the water used for preparation of hydrated lime (in terms of lime contamination) is generally not a problem unless the water contains more than 500 mg/l of sulphite, sulphate or bisulphite ions (Boynton, 1980).

The hydrated lime is prepared in a manner to keep the particle size to a minimum so that it will release the calcium ions more easily upon mixing with the tailings. This is achieved by ensuring rapid hydration. Rapid hydration occurs when there is sufficient water for reaction, the solution is mixed and the temperature is maintained in the range of 80 to 100 degrees Celsius. The exact slaking procedure will depend upon the quicklime used and thus the manufacturers recommendations for slaking should be followed (Boynton, 1980).

The procedure used for the test program was to add 3:1 water to lime by weight to obtain temperatures in the required range and to mix periodically by hand for a period of about ten minutes. After the reaction was complete and the temperatures had dropped, excess water was added to obtain a 10:1 water to lime ratio or a milk-of-lime mixture. Milk-of-lime is used as it will pour easily and is thus more convenient to mix with the tailings. The lime is slaked at least 30 minutes before use to ensure the slaking process is complete.

It is also noted that quick lime will slake in air due to moisture in the air and also after slaking will react with CO_2 in the air to form $CaCO_3$. This contaminates the quick lime and should be avoided by ensuring the product is sealed at all times. The hydration reaction is also a very explosive reaction if an amount of water approximately the same weight as the lime is added to the lime. The heat of reaction has been high enough to cause wood to burn. This means that quick lime should be stored where water will not be able to react with it. The hydrated lime mixture is also a corrosive base and should not come in contact with skin.

The acrylamide polymers come in either a dry crystal form or as a thick liquid. Cyanamid A-110 is a dry crystal. The polymer was mixed with distilled water at the concentration of 1 gram per litre, resulting in a viscous fluid. A large amount of water is required to allow the very long polymer molecules to expand and thus separate from each other. This allows them to be mixed into the tailings more easily. The polymer was mixed with water 24 hours before use and was not used if it had been mixed with water for more than 30 days as it tends to break down with longer residence times.

The only preparation required for sulphuric acid was to prepare a 10 percent solution from concentrated acid, as the 10 percent acid is not nearly as dangerous to handle as concentrated acid. The results are all based on 10 percent acid.

The hydrated lime or acid was poured into the tailings mixture being careful to not allow the lime or acid to be trapped in any surface bitumen. The tailings were then mixed for the required time. If polymer was added after lime addition, it was added for the last 30 seconds of mixing, as it is believed that longer mixing times will break up the long polymer chains, negating their effectiveness. The mixer speed was adjusted to just keep all of the tailings mixing, in an effort to keep mixing conditions uniform. It was found that the more the mixture was flocculated, the faster it had to be mixed due to the higher viscosity of the tailings. The viscosity of the tailings was not measured, thus the mixing energy was not calculated. The effect of mixing energy on the sedimentation and consolidation characteristics of the tailings is something that will have to be explored in further research.

3.3.2 Standpipe Tests

After mixing, the tailings were then allowed to settle undisturbed in the standpipes. With time, a clear supernatant appeared on the surface and the settlement of the tailings-supernatant interface was measured with a steel tape and recorded with the time since mixing stopped. Readings were taken frequently for the first two days and then only once a day for the remainder of the test. The average void ratio was calculated from the interface settlement curve and a void ratio versus time plot made. The manometers for the 2m standpipes were measured and recorded at the same time as the interface was measured. Plots of excess pore pressure with time for each manometer and the excess pore pressure isochrones (pore pressure versus height) were prepared.

At the end of the test, a water sample was collected and the sediment was removed from the standpipe in layers so that samples could be taken for water contents and grain size analyses. The layers were removed by carefully scooping them out with a ladle. The first 600 ppm 2 m column was sampled by drawing the tailings through a hose into a vacuum bottom, where samples were taken. This worked well for the top high moisture content zone, but not well for the bottom half of the sample, as the water was drawn out before the sand. The samples from the bottom were likely of too high moisture content because of this. The other 2 m standpipes have not been sampled yet.

One 2 m standpipe was loaded with the piston assembly shown in Figure 3.3. After the self-weight consolidation of the tailings was complete, the decant water was siphoned from the surface except for 4 cm to saturate the piston and reach a manometer port, where a hydrostatic reading could be taken for excess pore pressure calculations and for correcting the weight of the lead shot. The travel of the piston and the manometer readings were recorded with time. The weight of the piston assembly was used for the first load and lead shot placed on top of the piston was used for subsequent loads.

3.3.3 Consolidation Tests

3.3.3.1 Step Loading Consolidation Tests

The step loading tests were started after the tailings were allowed to sediment and consolidate from their self-weight in the test cylinder. The hindered settling and self-weight consolidation stages were essentially complete in two to four weeks. Pore pressure at the base and height of the sediment-decant interface were recorded during this stage. The supernatant was then drawn off from the sample except for a few cm left to saturate the drainage system. Following this, loads were applied to the sample using dead weights. The loads started at 1.25 kPa and were doubled from there. Each loading stage took one week to complete. The loads were calculated to include the friction of the piston on the cylinder wall.

The friction was determined by applying dead loads in increments to the piston until it started to move and then removing the load until the piston stopped moving. It was this lesser load that was added to the required load to get the total load.

From the consolidation portion of the test, plots of void ratio vs time and void ratio vs effective stress were obtained.

The permeability component on the experiment was performed between the loading stages. At the end of a loading stage, the piston rod was first clamped into place to ensure no movement during the test. The position of the piston was monitored with the LVDT during the tests and no movement was recorded. The top burette, that was connected to the base of the cell, was filled and connected to the hose, ensuring no air bubbles could be seen. The bottom burette was emptied and connected to the water filled hose such that a small amount of water entered into the burette. The vertical distance between the burettes was then adjusted to obtain the desired hydraulic gradient. Applied heads of just less than the previously applied pressures were used for the smaller loads unless this was not physically possible and then the largest head possible with the setup was used (80 cm). Heads less than the previous consolidation pressure were used to ensure that the permeability measurements did not affect the consolidation characteristics of the tailings.

The positions of the menisci in the burettes were then recorded and the valves opened to allow the water to flow. The amount of flow with time was recorded for both burettes and the average used for calculations. The test was stopped when the top burette was empty. The bottom valve was then closed, the bottom burette positioned for the consolidation experiment, the piston clamp removed and the next load applied. The result of the permeability test is a plot of void ratio versus hydraulic conductivity, along with the flow rate versus time plot.

At the end of the test, the sediment was sampled in five layers in the same manner as the standpipe tests. The samples were analysed for water content and fines content.

3.3.3.2 Constant Rate of Deformation Consolidation Tests

The constant rate of deformation tests were started after the hindered settling stage and the first part of the self-weight consolidation stage were complete. This required anywhere from three to ten days. The decant was siphoned off, except for two cm to saturate the drainage system. The piston was inserted into the cell and the samples were then loaded at a constant rate of deformation of 0.003 mm/min. The test was allowed to run until an effective stress of 100 to 200 kPa was reached. The average void ratio was determined from the displacement of the piston. The effective stress was calculated using the methods of Smith and Wahls (1969), Wissa et al (1971) and

Umehara and Zen (1980) as discussed in section 2.6.3. The total stress was calculated from the load on the piston (minus the friction determined in the previous section) in kN divided by the area of the piston in m^2. A drawback of this equipment is that there is no measurement of total stress at the base of the cell, and thus no way of knowing the amount of friction between the sediment and the cylinder wall. It was assumed to be negligible here, since it was not measured, but could be significant above stresses of 20 kPa, as measured by Pollock (1988). The effect of the friction, if not measured, would be to underestimate the amount of consolidation for a particular effective stress.

3.4 Tailings Properties

Two batches of total tailings were used for the testing program. The first batch was six barrels of tailings that were sampled during a field test of lime-spiked tailings by Syncrude. The limed tailings were produced by injection of lime slurry into the tailings pipeline at a rate of 1200 ppm $Ca(OH)_2$ based on total weight of the tailings. This represents 900 ppm CaO if the lime was completely hydrated. The barrels were filled after the limed tailings travelled through approximately 800 m of pipeline and an in-line booster pump. This represents about six minutes of mixing in the pipeline after lime injection. With the non-uniform nature of the tailings stream and the lime injection process, the exact amount of lime in the barrels was not certain, but was assumed to be 900 ppm CaO.

After arrival in Edmonton, the tailings had to be thoroughly mixed to extract them through the bung holes on top of the original barrels. The tailings then sat in new barrels until they were required for testing. It was observed that the tailings segregated into three zones after sitting in the barrels for a few months. The bottom zone consisted of mostly sand, the middle zone of mostly fines and the top zone of clear water. This is similar to the segregation observed at the Syncrude Mildred Lake tailings pond for untreated tailings. The conclusion from this is that the lime effect on the tailings had been destroyed by the mixing required to extract the tailings from the original barrels. These tailings were used for preliminary tests only as the fate of the original lime was not determined. The original dose of lime could have had an effect on the water chemistry of these samples as well as an effect on the sedimentation and consolidation tests.

The second batch of tailings was sampled directly from the plant five tailings line and did not have lime added. This batch was used for all final tests and the results compared to the results from the original batch. These tailings were first analysed to determine their initial properties before testing. These were water content, specific gravity, bitumen content, grain size and supernatant chemistry.

Table 3.1 lists the initial properties of the tailings, except the supernatant chemistry which is presented in section 4.3. The tailings are very similar except that the batch #1 tailings show a lower initial solids content and a wider range of solids contents between barrels. The properties of batch #2 tailings are remarkably uniform between barrels. The batch #2 tailings are typical of the average tailings stream, in terms of solids content and grain size, while the batch #1 tailings are closer to the lower end of the solids content range of the tailings stream.

Specific gravity was determined according to ASTM D854 methods, using partial vacuum to de-air the samples. Several samples were also de-aired by boiling and similar results were found. The bitumen content was determined using the modified method 2.7 "Determination of Bitumen, Water and Solids Content of Oil Sands" from Syncrude (1979). Toluene is filtered through the sample to extract the bitumen.

Figure 3.8 shows typical grain size curves for tailings batch #1, from both sieve and hydrometer. Figure 3.9 shows the grain size curves for the 18 initial samples taken from the six barrels from batch #2. Figure 3.10 shows the complete grain size for three of these initial samples, from both hydrometer and sieve. The grain size curves are all very similar, with about a 5 percent range for any

Table 3.1 Initial Properties of Tailings

	Tailings Batch #1	Tailings Batch #2
Initial Solids Content		
range	42.5 % to 49.7 %	53.2 % to 54.2 %
average	46.4 %	53.8 %
% Fines (<#325)		
range	16.9 % to 19.4 %	15.3 % to 18.9 %
average	18.2 %	16.8 %
D50 (mm)	0.11 to 0.12	0.11 to 0.12
Specific Gravity	2.67	2.64
Bitumen Content (% of dry Wt.)	0.73 %	0.64 %

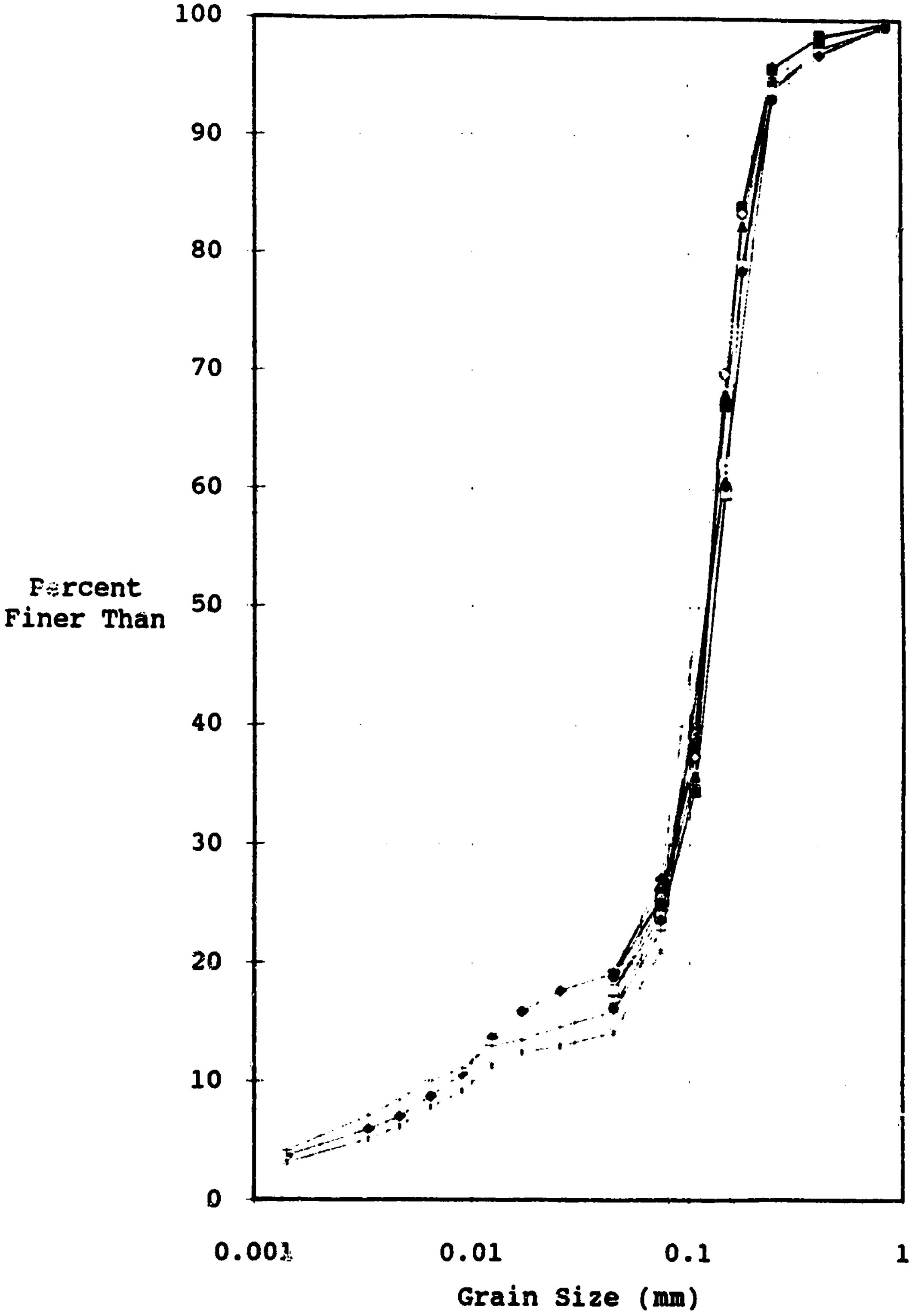


Figure 3.8 Tailings Batch #1 - Grain Size Distribution - Sieve and Hydrometer

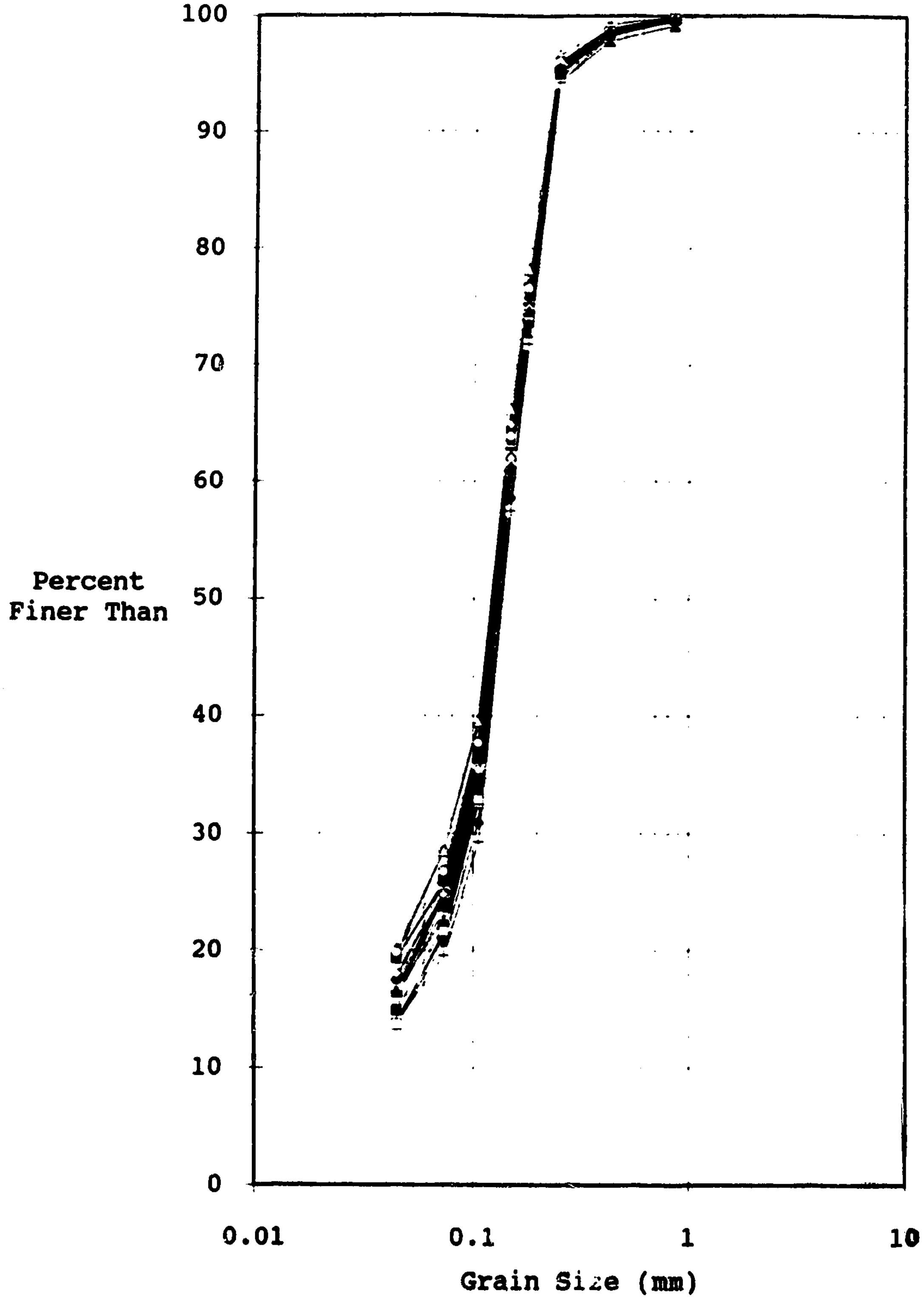


Figure 3.9 Tailings Batch #2 - Grain Size Distribution - 18 Initial Samples

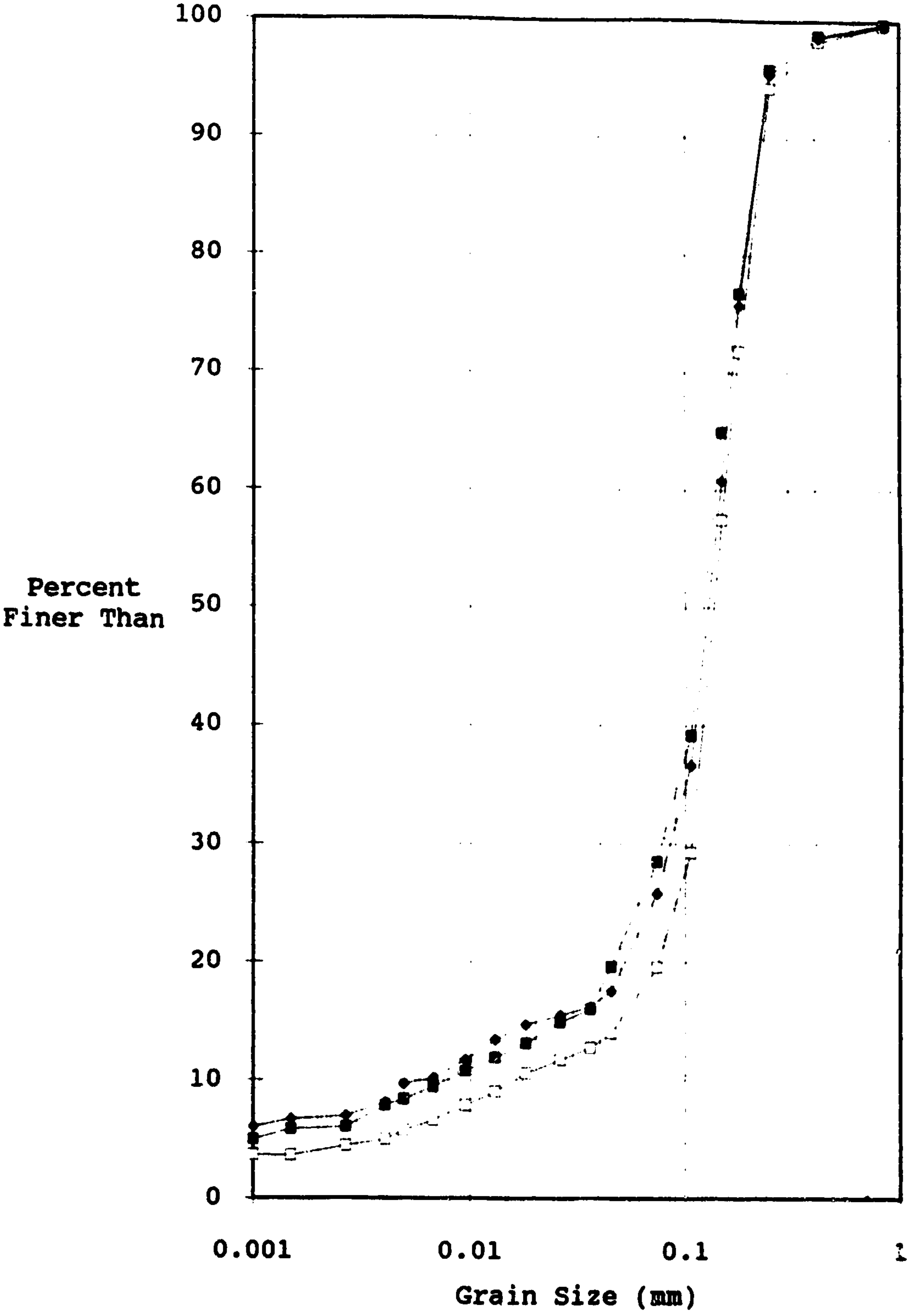


Figure 3.10 Tailings Batch #2 - Grain Size Distribution - Sieve and Hydrometer - Selected Initial Samples

particular grain size. This is more obvious for the fine sand-silt portion of the curve since it flattens out here.

Most of the initial grain size analyses were performed using sieves, with some hydrometers to verify the silt portion of the curve. For this research, the amount of fines based on the #325 sieve (0.044 mm) was selected to be the criterion for determining the amount of segregation of a mix. Thus, for the final samples taken from the tests, a complete grain size analysis was not performed, as the amount passing through a #325 wash sieve was sufficient to analyse the success of the test.

The sieve analyses were performed by first drying the material to get a dry weight, then soaking in water for 24 hours and mixing in a mixer for five minutes to break up the fines. The material was then washed through a #325 sieve, the retained material dried and weighed and then a stacked sieve used to obtain the sand grain size distribution. It was found that bitumen was not a problem for sieving, likely due to the small amount present and was found to clump up and be included with the coarser sand particles. No significant amount of fines could be seen with the bitumen lumps.

The preparation for the hydrometer samples was the same as for the sieve tests. The hydrometers performed on batch #1 tailings were of the minus #200 sample, while for batch #2 tailings, they were on the complete sample. The results are similar for the silt portion of the curve, but show a difference for the clay portion. The reason the results are similar is likely because most of the sand portion falls out of suspension in the first minute before the first reading is taken. The major effect is that a smaller than recommended sample of the fines is being tested, since most of the weight is in the sands.

Table 3.2 lists the tests performed on batch #1 tailings and Table 3.3 lists the tests performed on batch #2 tailings, with the overall results of the tests. The tests listed are the standpipe tests performed, and where CLT or CRD is shown in the test column, a step-load consolidation or constant rate of deformation test was performed after the standpipe test was complete.

Table 3.2 Tests Performed on Tailings Batch #1

Test	CaO (ppm)	A-110 (ppm)	Initial Void Ratio	Final Void Ratio	Length of Test (hours)
Barrel #1					
(a)	200	-	3.13	segreg.	2800
(b)	400	-	3.13	1.16	2800
(c)	600	-	3.13	1.32	2800
(d)	1600	-	3.13	1.65	2800
(e)	3200	-	3.13	1.61	2800
Barrel #2					
SLT (a)	600	-	3.14	1.19	305
(b)	600	6	2.91	0.9	1035
(c)	600	6	2.89	0.95	1008
(d)	600	6	2.89	0.95	988
Barrel #3					
(a)	600	-	2.94	1.04	1780
CRD (b)	600	-	3.23	1.38	451
(c)	600	6	2.97	1.11	1780
Barrel #4					
CRD (a)	600	-	2.59	1.4	314
Barrel #4,#5					
(a)	600	6	2.94	1.66	242
(b)	600	6	2.94	1.56	242
(c)	600	6	2.94	1.55	242
Barrel #5					
(a)	600	-	3.72	1.9	335
(b)	600	-	3.78	1.94	335
(c)	600	-	3.48	1.79	335
(d)	600	-	3.35	1.68	335

Table 3.3 Tests Performed on Tailings Batch #2

Test	CaO (ppm)	A-110 (ppm)	Initial Void Ratio	Final Void Ratio	Length of Test (hours)
Barrel #1					
(a)	400	-	2.39	segreg.	2230
(b)	600	-	2.25	0.88	2230
(c)	800	-	2.31	0.89	2230
(d)	1200	-	2.23	0.94	2230
(e)	1600	-	2.3	0.97	2230
Barrel #2					
(a)	800	3	2.31	0.92	2110
(b)	800	6	2.21	0.87	2110
(c)	800	12	2.25	0.93	2110
CRD	800	-	2.25	1.09	97
CRD	600	-	2.28	1.29	241
Barrel #3					
2 m	800	-	2.24	0.88	1248
CRD	800	-	2.24	1.01	126
SLT	800	-	2.24	0.91	244
Barrel #4					
2 m	600	-	2.25	1.05 (seg)	1080
.477 m	600	-	2.25	0.88	1250
Barrel #5					
2 m	600	-	2.33	1.05 (seg)	1464
.56 m	600	-	2.33	0.94	960
Barrel #6	H_2SO_4 ml/l				
(a)	7.5	-	2.31	1.18	600
(b)	10	-	2.3	1.02	600
(d)	12.5	-	2.37	1.31	600

4. Test Results

The test results are presented in two sections, one for each batch of tailings. For each, the standpipe results are presented first, followed by the consolidation results. The water chemistry results are presented at the end in section 4.3.

4.1 Tailings Batch #1

4.1.1 Standpipe Tests

The first five standpipe tests performed on tailings batch #1 were to determine the optimum lime content in terms of sedimentation rate, consolidation rate and average void ratio after self-weight consolidation. Concentrations of CaO of 200, 400, 800, 1600 and 3200 ppm based on total weight of the tailings were used. The results in terms of average void ratio versus time are plotted in Figures 4.1 and 4.2. Figure 4.1 shows the first 300 hours of the tests and Figure 4.2 shows the complete duration of the tests up to 3000 hours. It is emphasized that the plots are in terms of average void ratio and that the void ratio will vary non-linearly through the sample and will generally be much higher at the top of the sample.

The column containing 200 ppm CaO segregated indicating an insufficient amount of lime to cause enough aggregation of the clays to keep the sand particles from falling to the base of the cylinder. A sand layer could be felt with a steel tape about half way down the cylinder, whereas in the

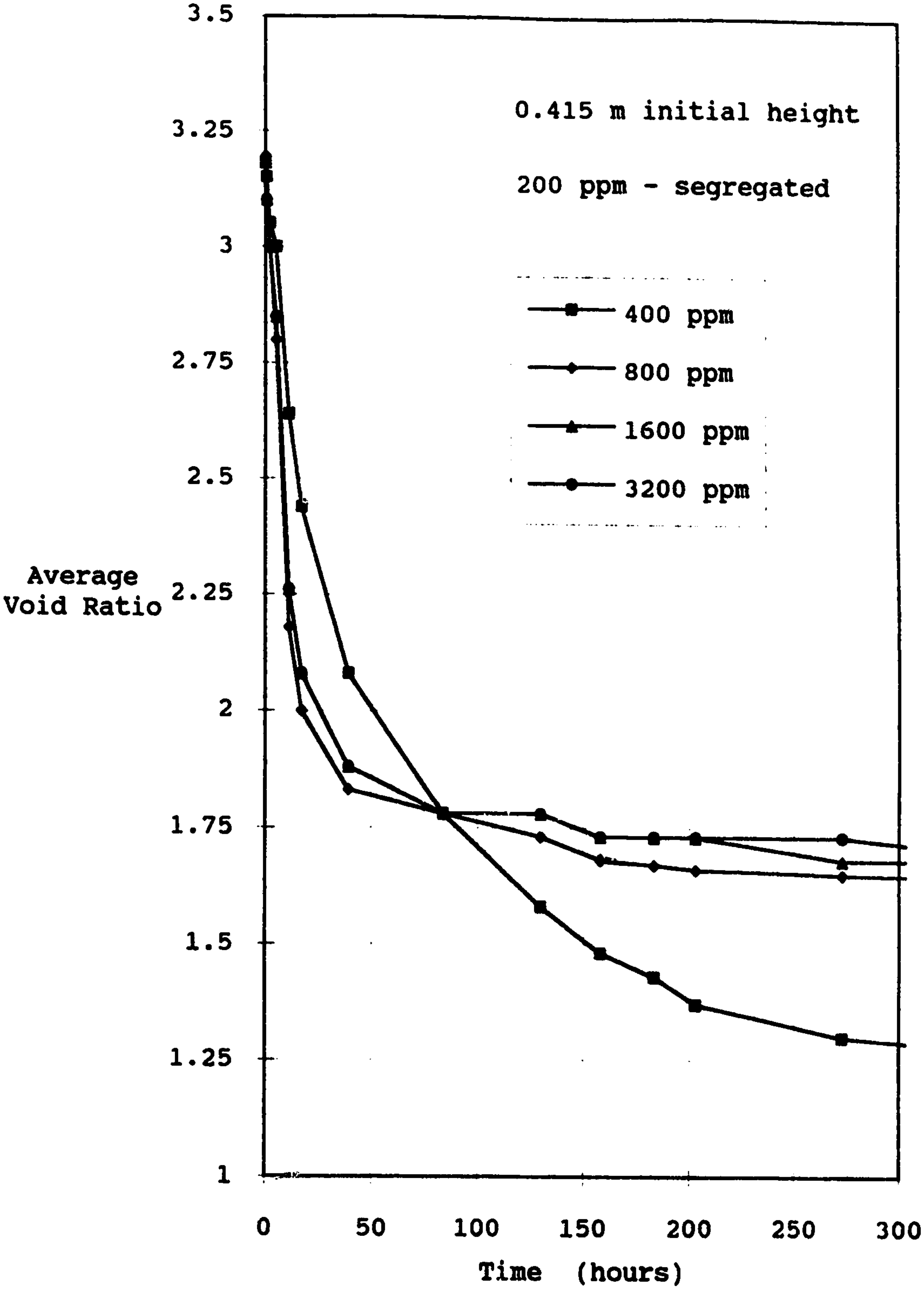


Figure 4.1 Tailings Batch #1 - Variable Lime Content Standpipe Tests to 300 Hours

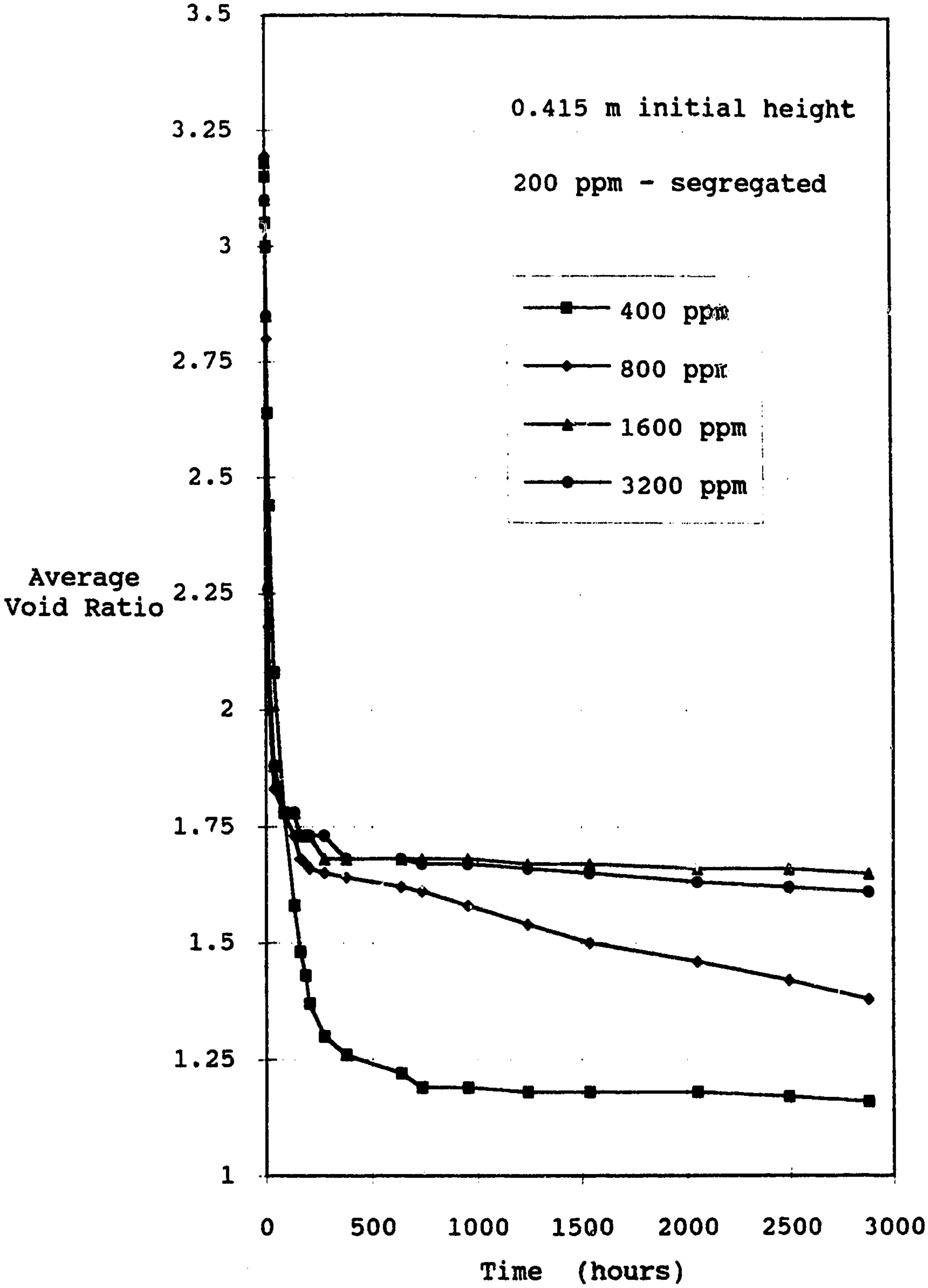


Figure 4.2 Tailings Batch #1 - Variable Lime Content Standpipe Tests to 3000 Hours

other cylinders no change in density could be felt with a tape for the full height of the cylinder. It was also observed that a layer of bitumen formed on the surface of the 200 ppm test and no clear water appeared on the surface, below the bitumen, until a week had passed. The bitumen in the other tests was trapped in the sediment and only a sheen of hydrocarbon on the surface was observed.

The plots show that the 1600 and 3200 ppm CaO mixes sedimented more rapidly but that the average void ratio after self-weight consolidation was much less than the 800 and 400 ppm CaO mixes. The results also show that the 400 ppm mix sedimented and consolidated to a significantly lower average void ratio than the 800 ppm mix.

The moisture content profiles for the four non-segregating mixes are shown in Figure 4.3. The data is limited, but shows a trend of increasing water content with increasing lime content, and a layer of higher water content tailings on top of the sediment for the 400 and 3200 ppm tests. The observations during the sampling were that the 3200 ppm test, and to a lesser degree the 1600 ppm test, were stiffer and harder to pour than the 400 and 800 ppm samples, even though their water contents were higher. The 800 ppm, 1600 ppm and 3200 ppm tests also showed an off white crust on the surface of the water after the samples had been sitting for a few weeks. This crust was removed and found to react with 10 % hydrochloric acid in the

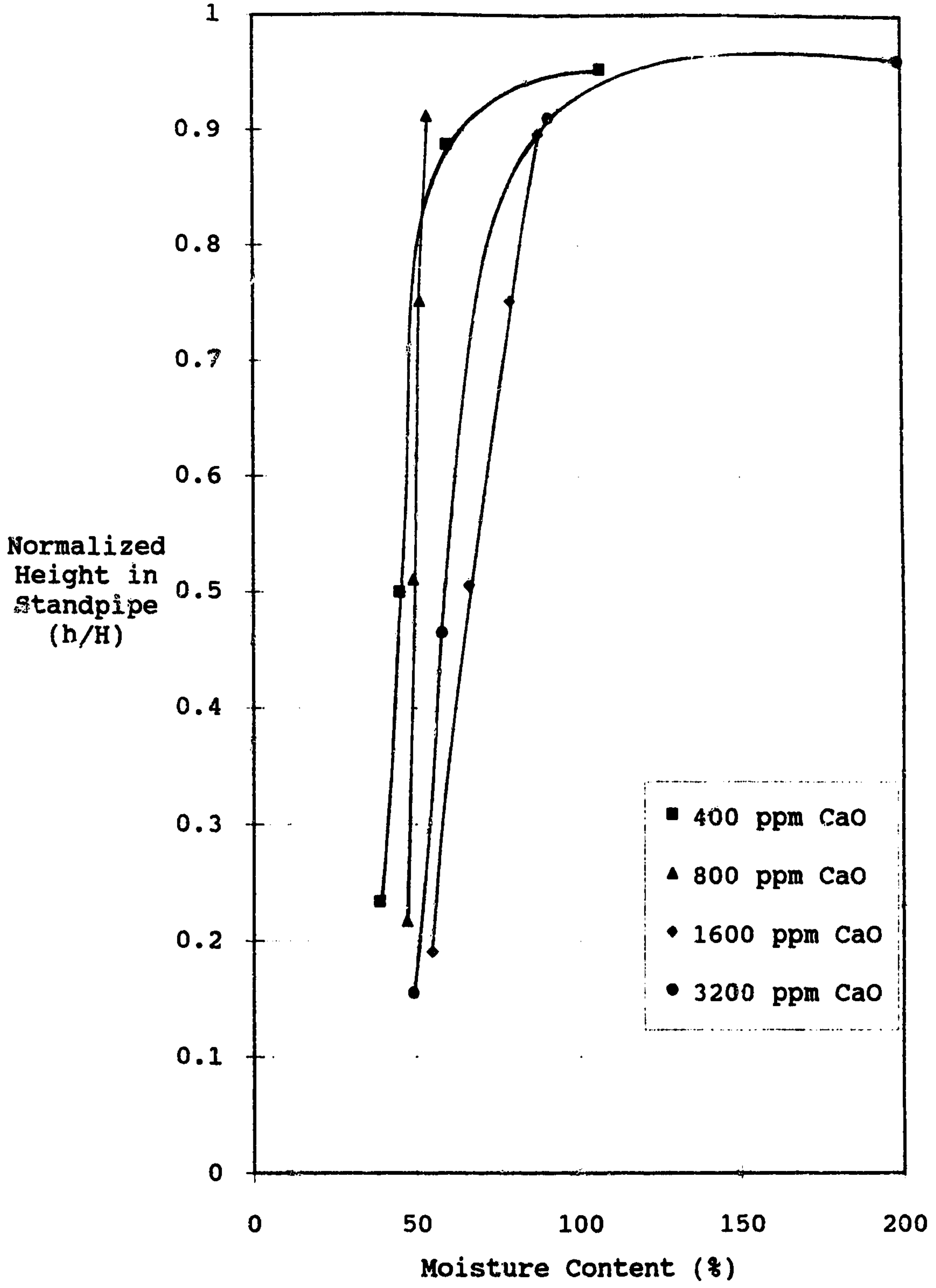


Figure 4.3 Tailings Batch #1 - Moisture Content Profiles After Self-Weight Consolidation - Variable Lime Standpipe Tests

carbonate likely formed by the reaction of hydrated lime with bicarbonate in the tailings water by the reaction:

$$Ca(OH)_2 + HCO_3^- \dashrightarrow CaCO_3 + OH^- + H_2O$$

This will be discussed further when the water chemistry is reviewed in section 4.3.

The results of the first set of tests seem to indicate that there is an optimum lime concentration in terms of settling and self-weight properties of the tailings. Too low lime concentration results in insufficient flocculation of the clays and too high lime concentration results in a clay floc structure that is too strong in that it resists the self-weight consolidation of the tailings.

From the results of these tests and the results of similar tests by other workers (C-H Synfuels, (1984), Fuhr and Liu, (1981), Fuhr, Sanford and Lemke, (1982) and Liu, Lane and Cymbalisty, (1980)), an optimum lime concentration of 600 ppm was chosen for further work on the first batch of tailings.

The next set of standpipe tests performed on the first batch of tailings are eight tests with 600 ppm CaO. These were performed in either the 0.6 m PVC cylinders or in the stainless steel cylinders. The ones performed in the steel cylinders were the self-weight stages of the consolidation tests. The plot of average void ratio versus time for all the tests is shown in Figure 4.4

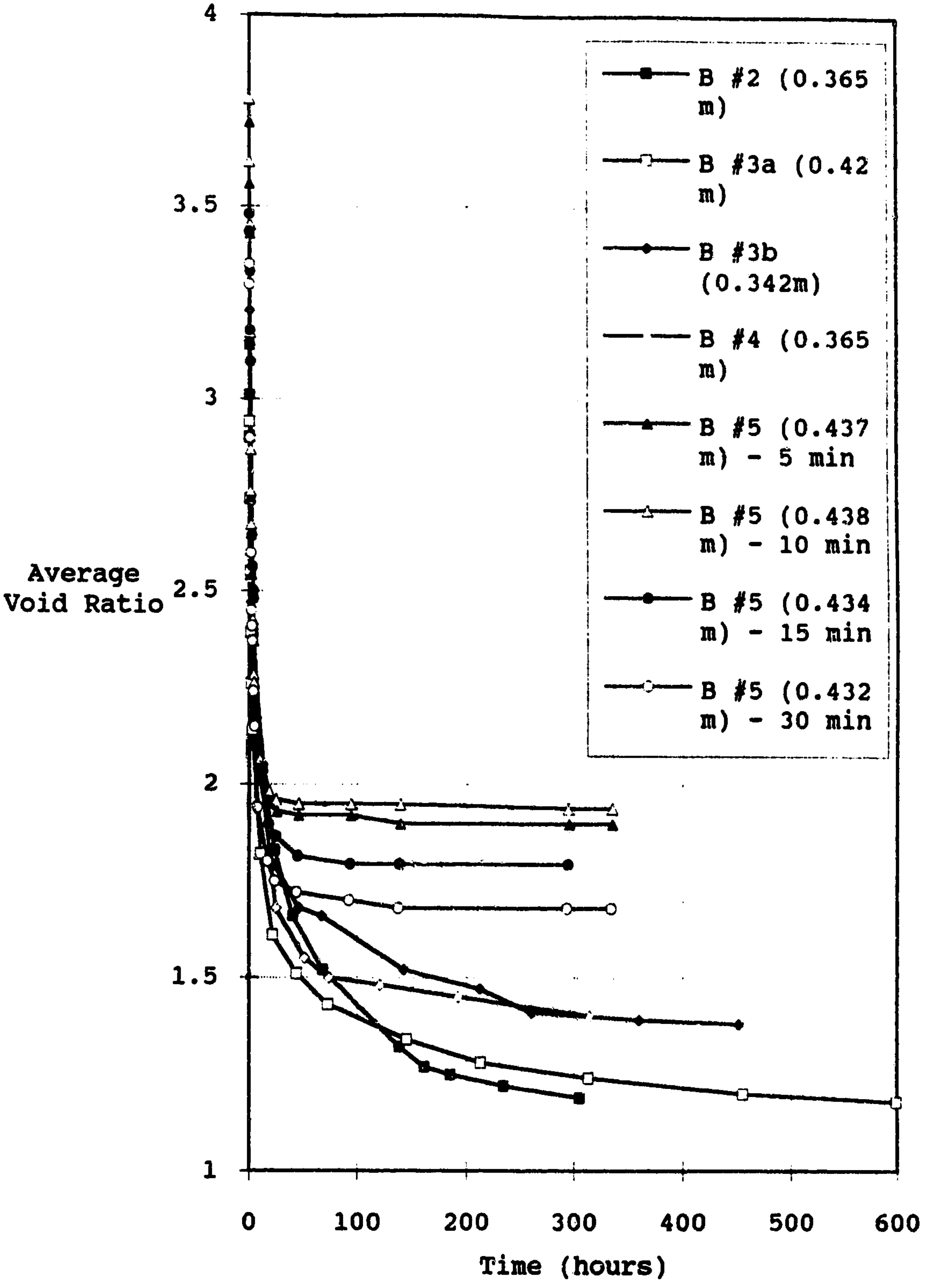


Figure 4.4 Tailings Batch #1 - 600 ppm CaO Standpipe Tests

What is immediately obvious from looking at the plot is the wide variation in final void ratio between tests. This variation is likely due to several reasons, including the large variation in initial void ratio, the original lime added by Syncrude, the clay content of the samples and the mixing conditions.

The widest variation between samples appears to be dependent on the barrel that the sample came from. The fines content measurements after settlement (Fig. 4.6) show that the barrel #5 tailings partially segregated, likely due to the lower initial solids content (41% - 44%) of this barrel compared to the other barrels (46% -50%). The moisture content after self-weight consolidation plot (Fig. 4.5) also shows the barrel #5 tests to have a much higher overall water content, as well as a much higher water content at the top. The consolidation test samples were not analysed for water content or fines content as the samples were consolidated following the standpipe test.

The barrel #5 tests may indicate a lower boundary in terms of solids content where flocculating the clays by adding lime is insufficient to stop segregation (at least for lime concentrations of 600 ppm). More testing is required to further prove this hypothesis.

The chemical analysis of the decant (Table 4.2 - discussed in section 4.3) also shows that the barrel #5 samples had higher pH and OH- levels compared to the barrel

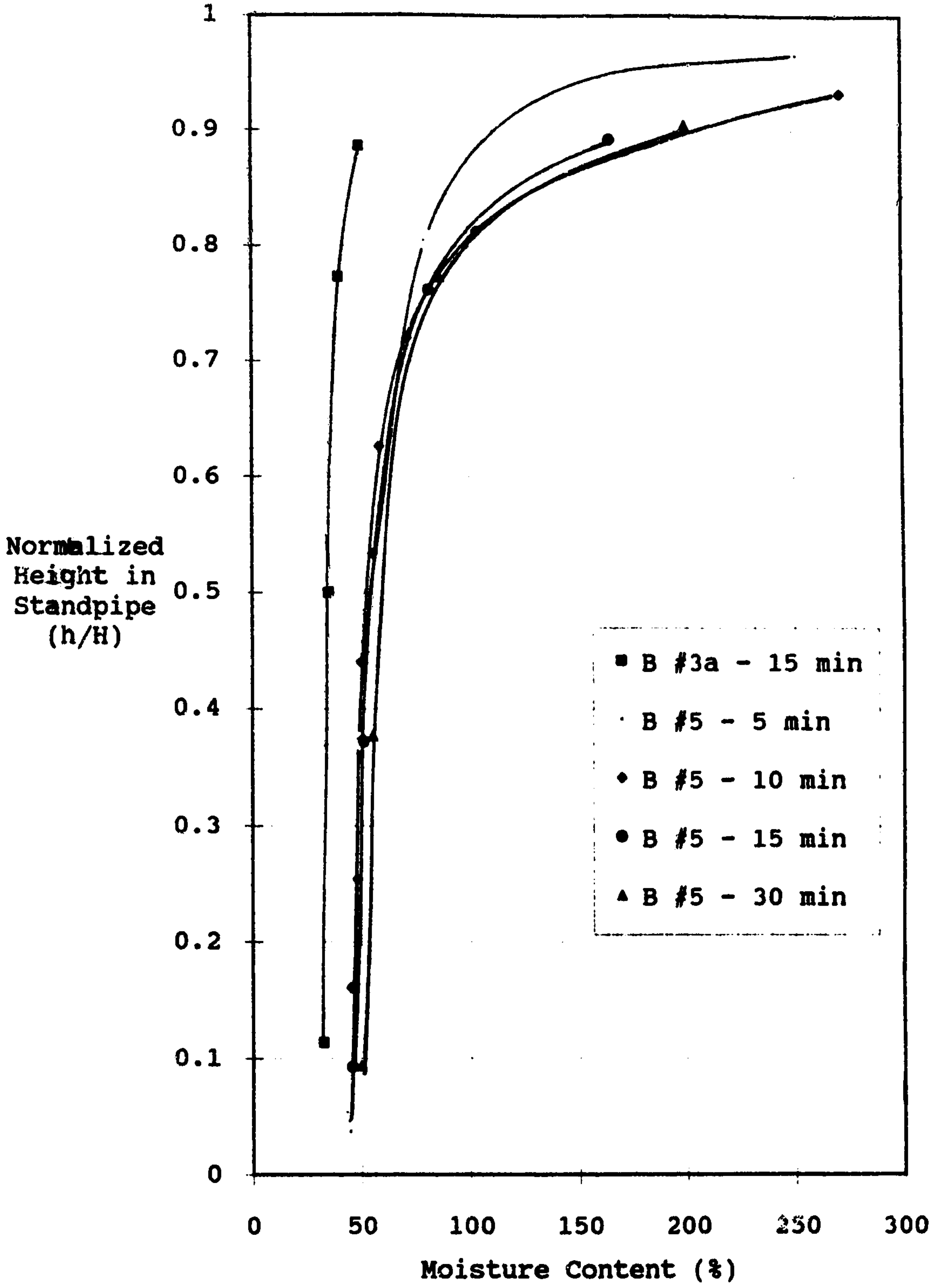


Figure 4.5 Tailings Batch #1 - Moisture Content Profiles After Self-Weight Consolidation - 600 ppm CaO Tests

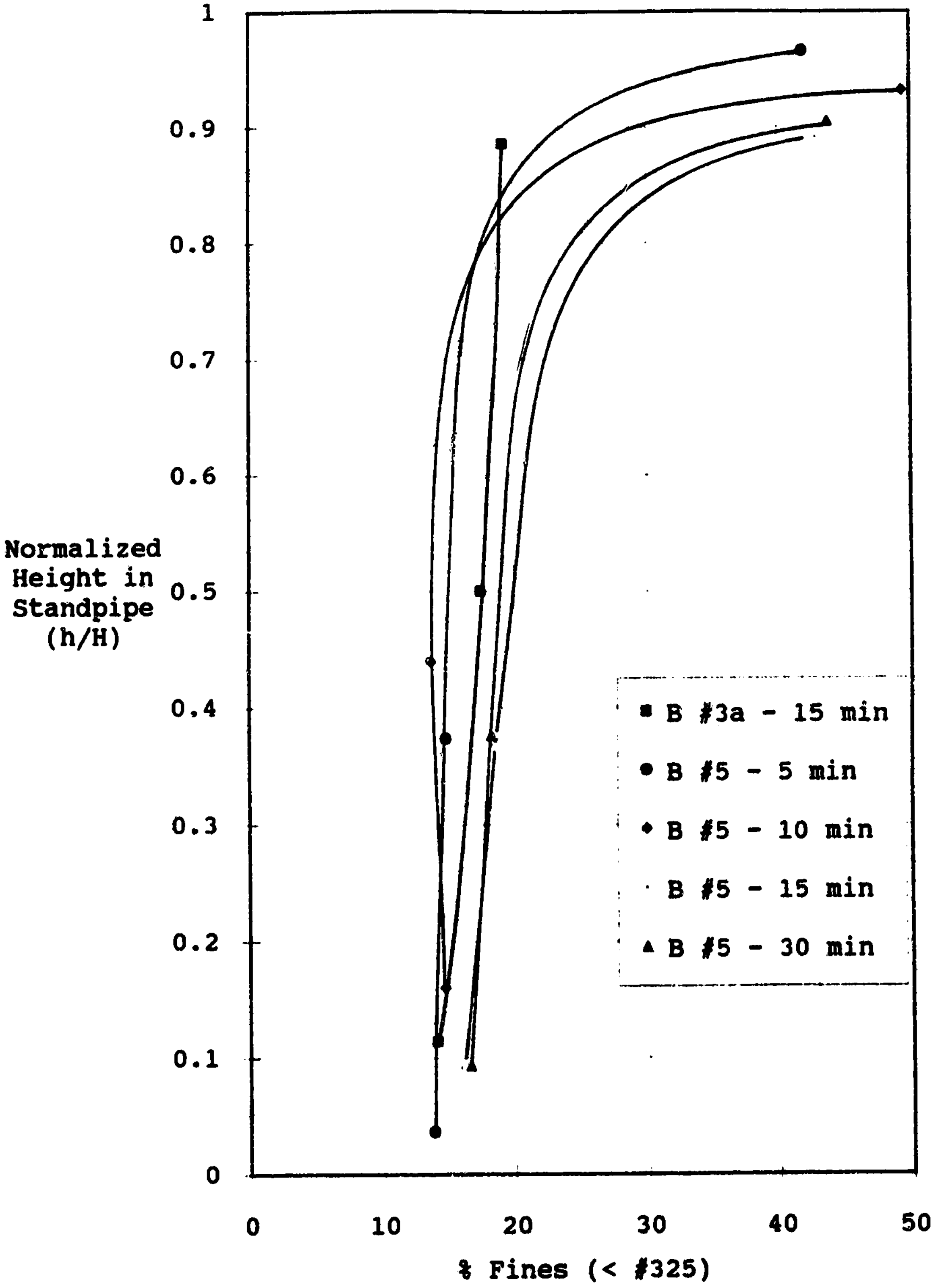


Figure 4.6 Tailings Batch #1 - Fines Content Profiles After Self-Weight Consolidation - 600 ppm CaO Tests

tests also had a skim of $CaCO_3$ on the surface. This indicates that a significant amount of lime was used in the reaction with the bicarbonate in the water. Further testing is required to determine if better sedimentation and consolidation characteristics can be achieved with the lower solids content tailings.

The barrel #5 tests were to study mixing time, but since the samples segregated, the effect of mixing time cannot be determined.

The scatter between the other 600 ppm tests is possibly a result of the very small effective stresses present, where small changes in properties such as floc strength can significantly change the settled void ratio.

The next set of tests examine the effect of the polymer Cyanamid A-110 combined with lime on the settlement and self-weight consolidation of the tailings. The average void ratio versus time plot for the seven tests performed is shown in Figure 4.7. The tests labelled barrel #4,5 are of tailings from barrel #4 and barrel #5 combined. All tests contain 600 ppm lime, with concentrations of 3 to 12 ppm A-110 as shown in the figure.

The results again show a scatter with the tailings from barrel #4 and #5 combined showing a higher final void ratio, although the tests were cut short to begin testing on tailings from batch #2. The combined tailings had an initial solids content very similar to the other tests from

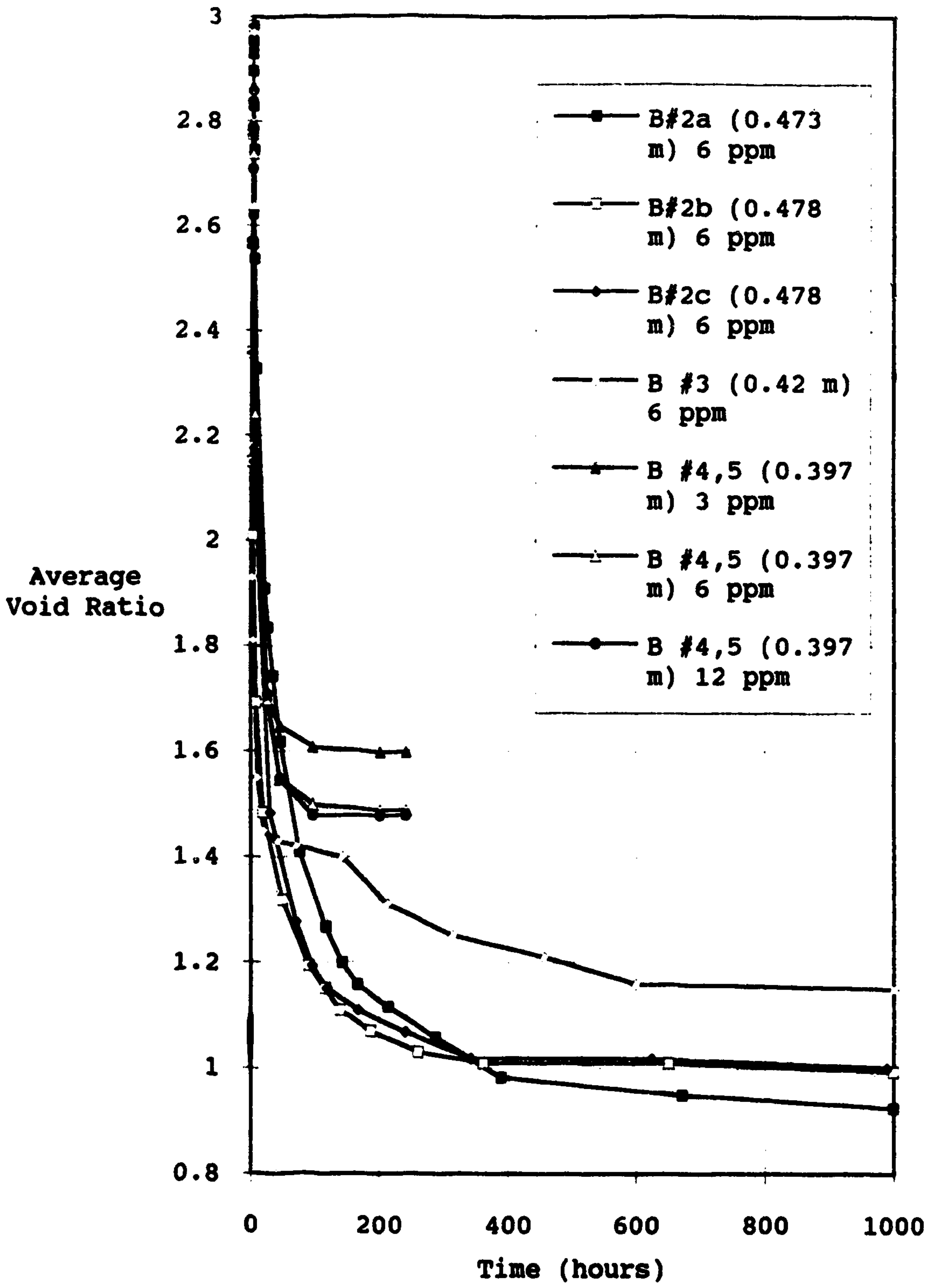


Figure 4.7 Tailings Batch #1 - 600 ppm CaO + A-110 Standpipe Tests

fines content profiles (Fig. 4.9) or water content profiles (Fig. 4.8). The barrel #4 and #5 tests showed a $CaCO_3$ crust and higher pH similar to the 1600 and 3200 ppm tests, indicating an excess of lime in the supernatant fluid. These tests also had a slightly higher fines content than average (19-20%). This could result in a floc structure strong enough to resist the low effective stresses generated at these small thicknesses. It is possible that this structure would break down with time or with a slightly higher effective stress as discussed in section 4.2.1. This is indicated by the initial height of the tests, as shown in Figure 4.7. The barrel #2 tests were 10 cm higher than the barrel #4,#5 tests, possibly resulting in enough effective stress to collapse the structure. The barrel #3 test appears to be just at the borderline, as it displays a non-uniform consolidation rate.

The polymer was found to be difficult to mix as it tended to want to float to the surface and cling to the mixing rod. This was complicated by the assumption that the long polymer chains would break apart with the prolonged mixing that would be required to completely mix the polymer with the tailings.

The overall conclusion is that A-110 does result in a slightly lower average void ratio when used with 600 ppm lime, but certainly not enough to justify the extra cost. It is possible that A-110 would give better results with

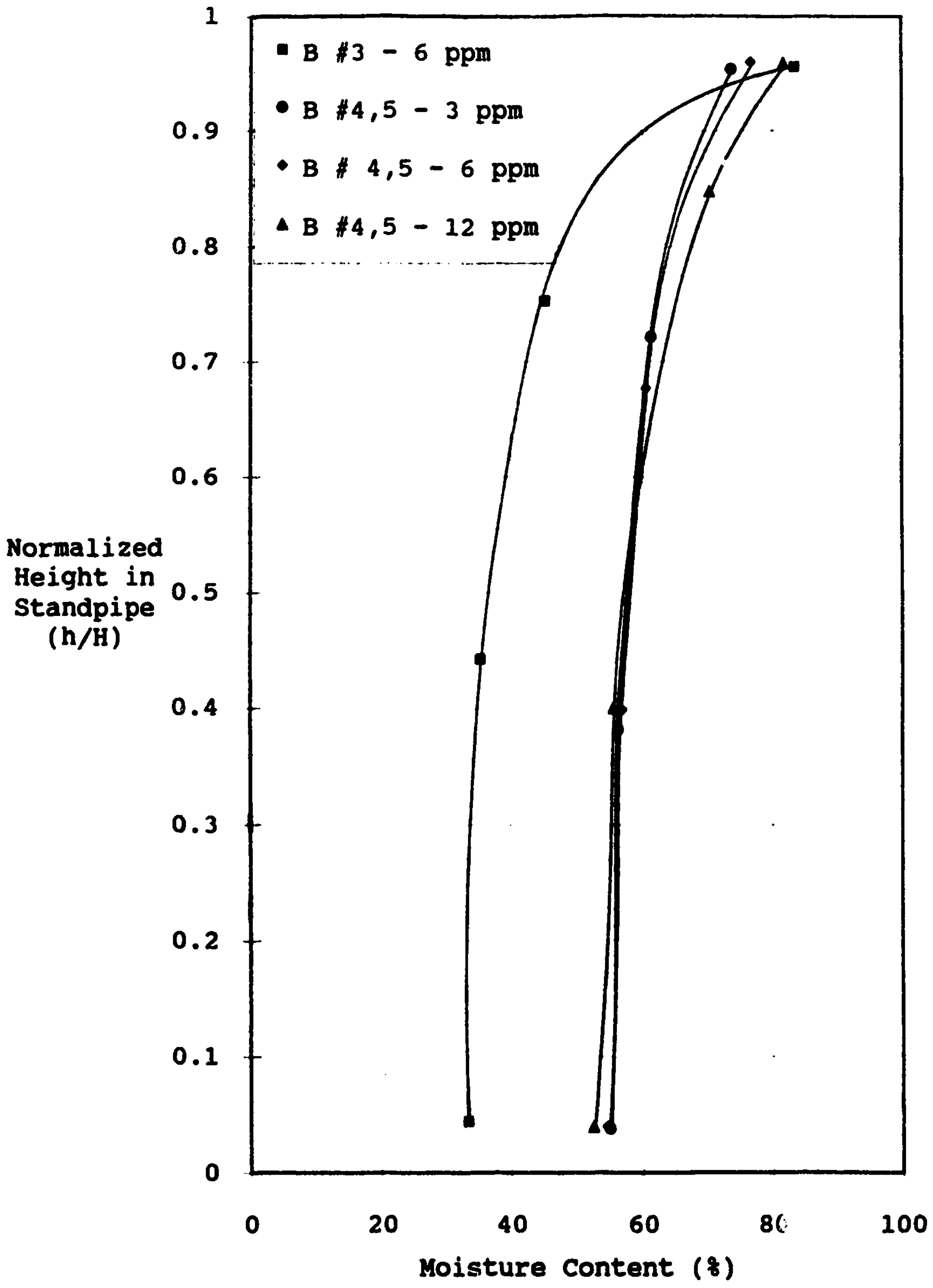


Figure 4.8 Tailings Batch #1 - Moisture Content Profiles After Self-Weight Consolidation - CaO + A-110 Tests

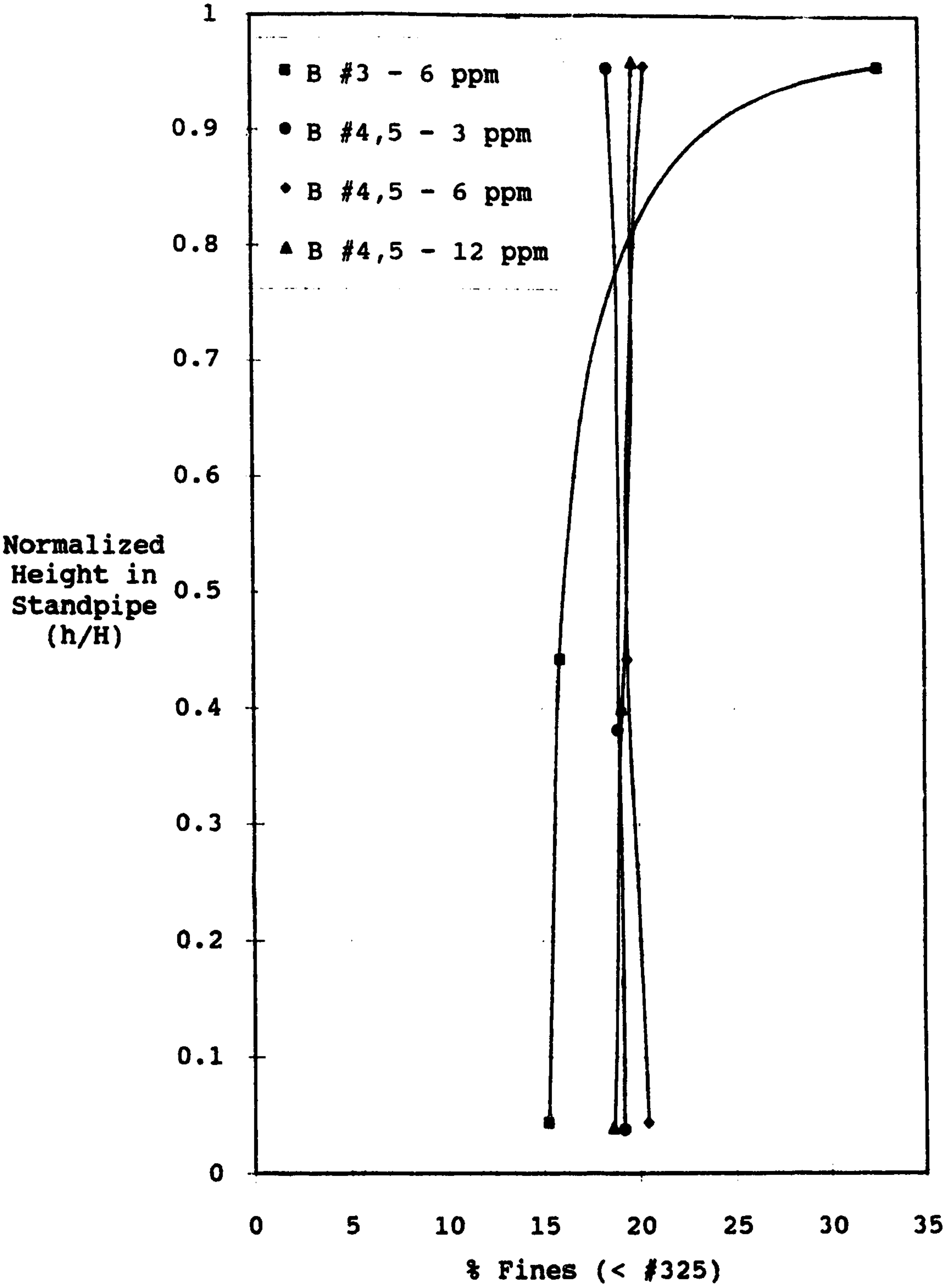


Figure 4.9 Tailings Batch #1 - Fines Content Profiles After Self-Weight Consolidation - CaO + A-110 Tests

lower concentrations of lime and this will be determined for batch #2 tailings.

4.1.2 Consolidation Test Results

4.1.2.1 Step Load Consolidation Test Results

One step load slurry consolidation test was performed on batch #1 tailings. It was performed on tailings with 600 ppm CaO added based on total weight. The average void ratio versus time plot for the self-weight consolidation and step loads is shown in Figure 4.10. The individual void ratio - effective stress plots are in Appendix B (Fig. B.1 to B.6). It is interesting to note that the strain due to the sample self-weight is much larger than the strains due to the applied loads. The strains also become smaller with each successive load, which can be seen on the void-ratio effective stress curve in Figure 4.11 where the curve dramatically flattens out around an average void ratio of 0.8. This is deduced to be the point at which sand grains begin to come in contact. This agrees with the slurry properties diagram for oil sand tailings (Fig. 4.12, from Scott and Cymerman, 1984) which shows for 18 % fines a sand matrix occurs at 78 % solids or a void ratio of 0.75.

The individual plots show that the curves had not completely levelled off for some of the loads. This is also exaggerated by the narrow shape of the plots. Since a limited amount of time was available for the testing

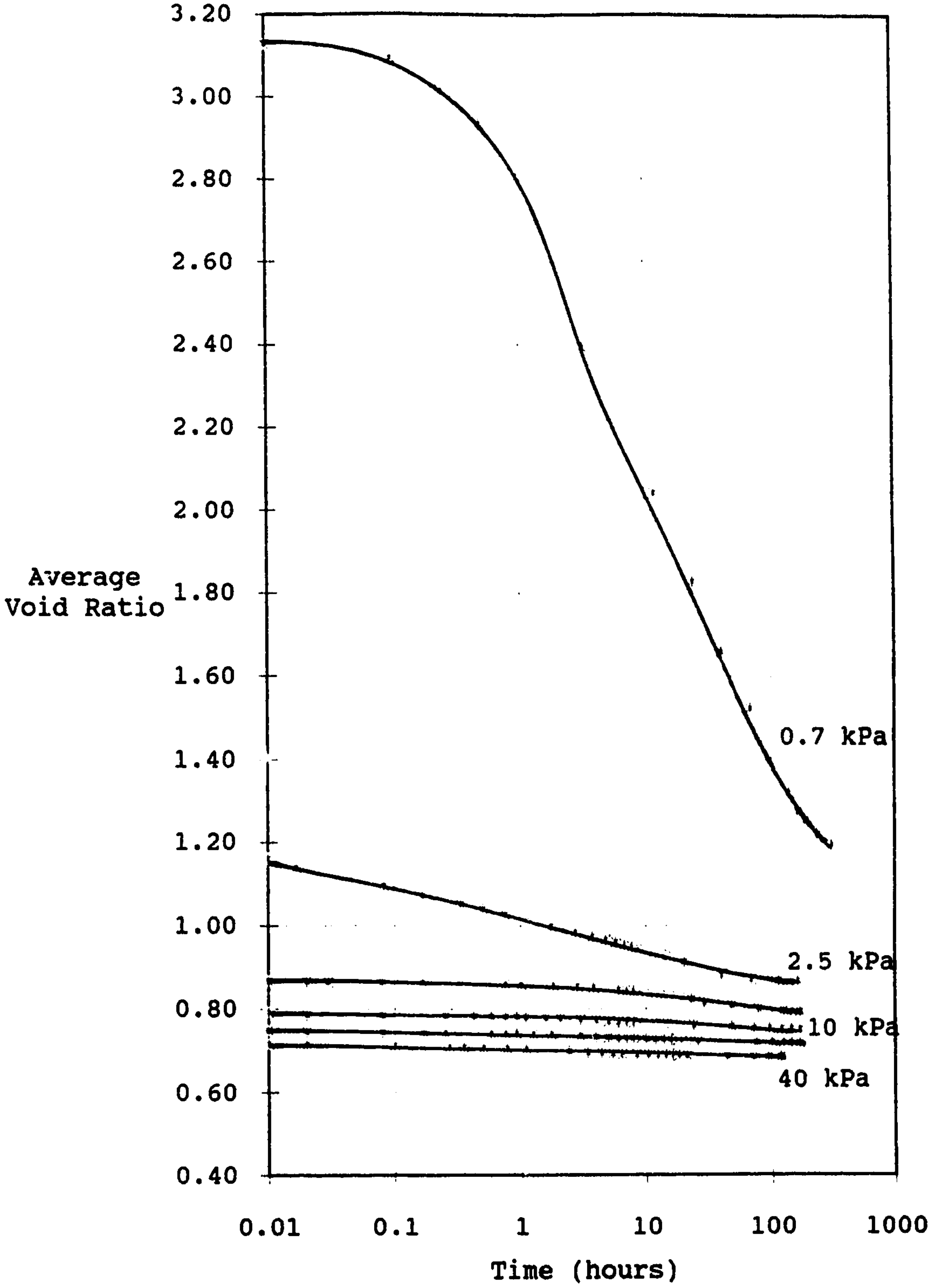


Figure 4.10 Tailings Batch #1 - Step Loading Consolidation Test

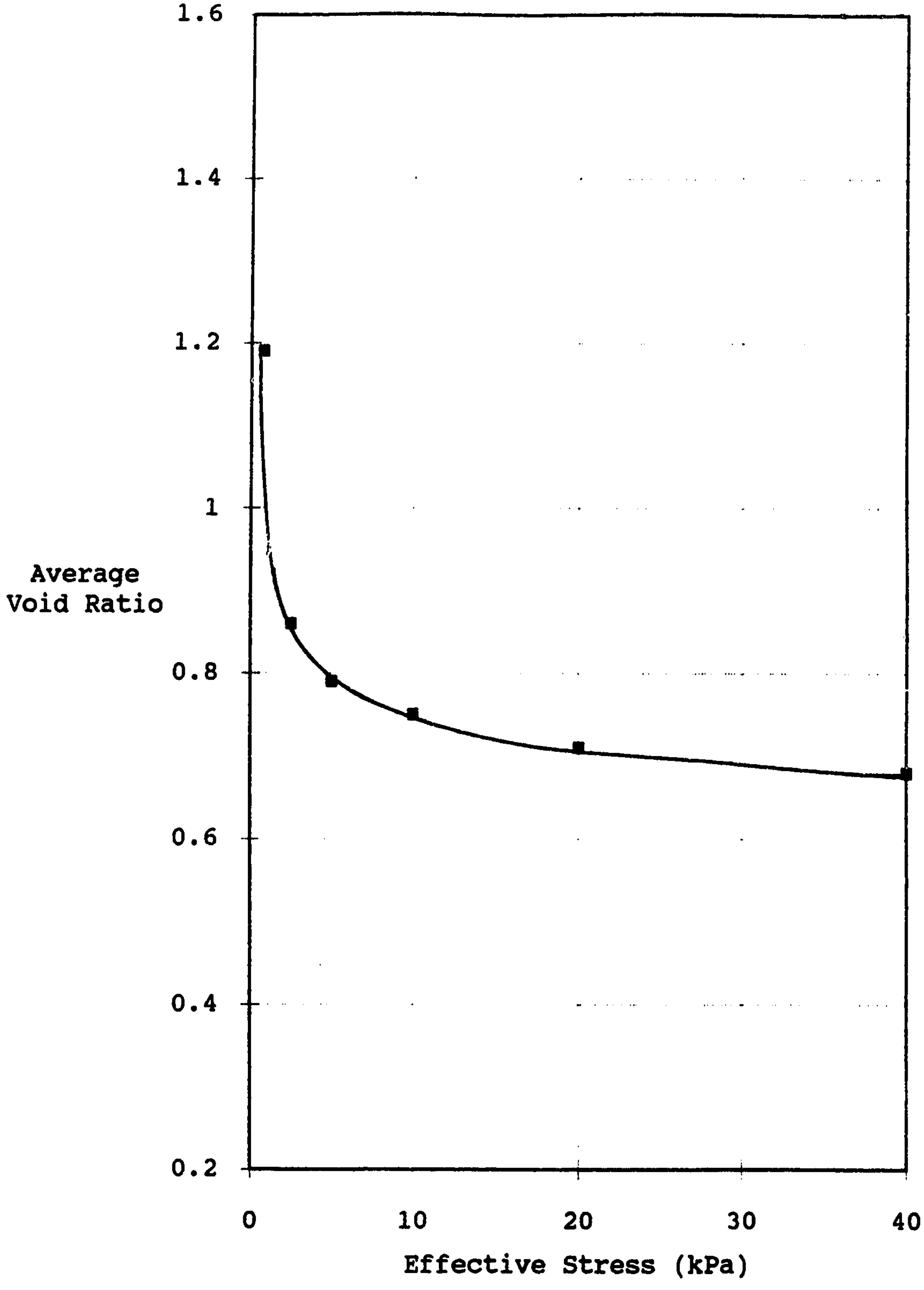


Figure 4.11 Tailings Batch #1 - Step Loading Consolidation Test

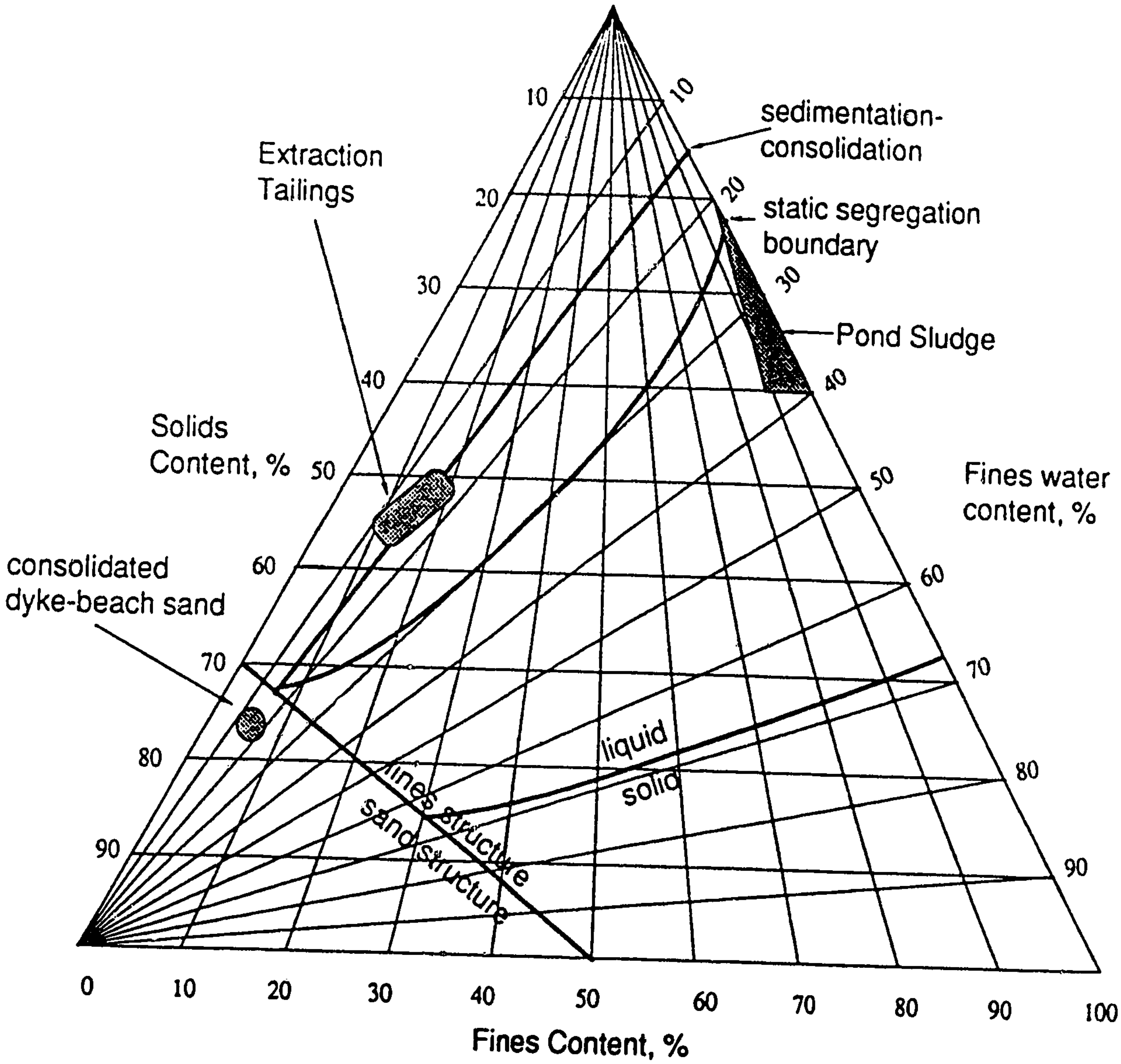


Figure 4.12 Slurry Properties Diagram for Oil Sand Tailings (from Scott and Cymerman, 1984)

each load, even though consolidation was not quite complete for some of the loads. This is further complicated by the large amount of secondary consolidation that appears to occur here.

The excess pore pressures at the base of the cell are plotted for each load increment in Appendix C (Fig. C.1 to C.6). The plots show that generally an initial excess pore pressure equal to the change in total stress occurs within the first hour, followed by a rapid decrease in the pore pressure to levels of 10 to 20 % of the change in total stress. The observation that the pore pressures dissipate faster than the void ratios level off indicates that a significant portion of the consolidation is due to secondary compression. This would also be the reason that the void ratio - effective stress curves were not levelling off with time, as they were following a secondary compression line.

Permeability was not measured between the loading stages, as was done for the constant load test for batch #2 tailings.

4.1.2.2 Constant Rate of Deformation Consolidation Test Results

Several constant rate of strain tests were attempted on tailings from batch #1, but due to equipment problems only one test was completed. This again was performed on tailings with 600 ppm CaO by total weight added. The completely seal in the large cylinder and most of the drainage came from around the edge of the piston. The smaller stainless steel cylinder which did not leak was used for tailings batch #2 tests and the results will be compared when those tests are discussed in section 4.2.2.2.

The methods of Smith and Wahls (1969) (non-linear) and Wissa et al (1971) were used to analyse the test. The method of Umehara and Zen (1980) was tried and found unacceptable, as the charts included with the method do not work when the initial void ratio is not uniform. The average void ratio versus effective stress from the first two methods is shown in Figure 4.13 and again shows a flattening of the curve at a void ratio about 0.8. The two curves of the Smith and Wahls (1971) analysis cover the possible range of the constant b/r. The plot shows that the three analyses result in approximately the same curve.

The void ratios for the same effective stress are somewhat higher for the constant rate test, possibly due to rate effects or secondary consolidation in the step load test. The plot shows that the tailings collapse with stresses of 1-2 kPa until a void ratio of 0.9 is reached.

For the portion of the test above a void ratio of 0.8, it is noted that the excess pore pressure at the base of the sample (Fig. C.7) ranged well above the recommended 3-20 % by ASTM D4186 for constant strain rate tests or the recommendation of Smith and Wahls (1969) that pore pressures

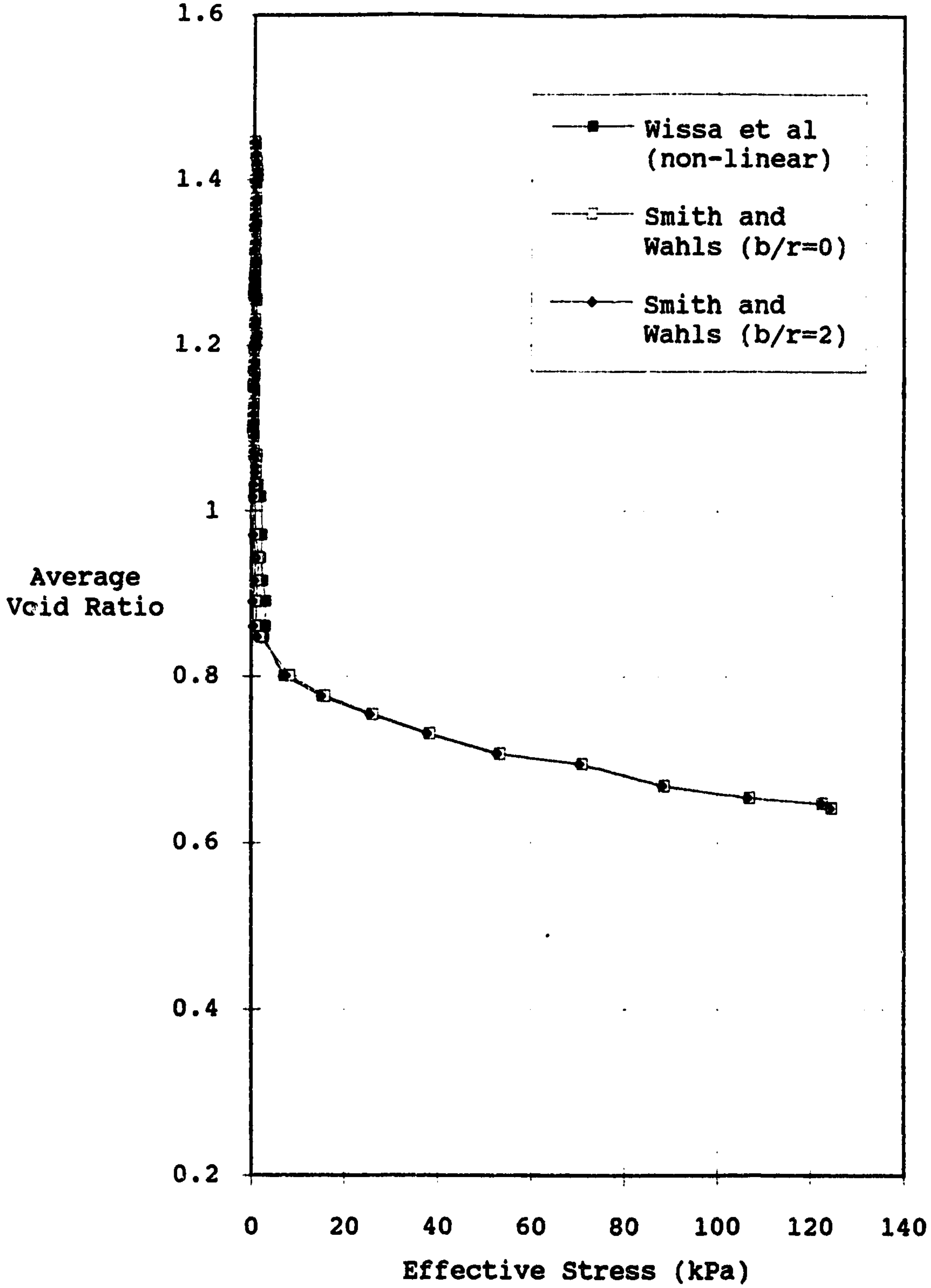


Figure 4.13 Tailings Batch #1 - Constant Rate of Deformation Consolidation Test

pressure increased approximately linearly with the total stress as though the material behaved as a fluid. This would tend to make the results of the experiment suspect. Lower strain rates were used for the tests on batch #2 tailings, to determine if the material can be consolidated without the large excess pore pressures.

4.1.3 Summary of Tailings Batch #1 Tests

The results for batch #1 tailings are quite scattered. This is likely due to two reasons: 1) the variability of the initial solids content between tests, 2) the magnitude of the self-weight of the samples and 3) the effect of the lime initially added by Syncrude.

There is an optimum lime content, in terms of standpipe tests, of about 600 ppm CaO by total weight for a 48 % solids content tailings. This may have to be increased for lower solids contents (below 45 %) or 45 % solids is a lower limit to the effectiveness of lime to limit segregation. An average void ratio after self-weight consolidation of 1.1 to 1.2 is obtainable with a solids content of 48 % for a 0.45 m initial thickness deposit.

The polymer A-110 does not appear to greatly enhance the settlement and consolidation characteristics of the tailings and has mixing problems.

The consolidation curves show that the flocculated tailings will collapse with effective stresses of only 1 to structure is reached the effective stress for a change in void ratio then rises rapidly, although significant changes in void ratio could occur for longer time periods at constant effective stress due to secondary compression.

4.2 Tailings Batch #2

4.2.1 Standpipe Tests

The first five standpipe tests performed on the second batch of tailings were to determine the optimum lime concentration in terms of settling and consolidation properties. The results are plotted in Figure 4.14. The moisture content profiles after self-weight consolidation are shown in Figures 4.15 and 4.16. The fines content profiles are given in Figure 4.17. It was found that 400 ppm CaO is insufficient to stop segregation of the tailings. As can be seen on the moisture content and fines content profiles for the 400 ppm test, there are definite sand and sludge layers formed, with much less fines trapped in the sand layer. It is interesting to note that although all four tests took different paths to get there, they all finished self-weight consolidation with very similar average void ratios (0.9 - 1.0). The moisture content and fines content profiles are also very similar except the 1200 and 1600 tests showed a slight increase in fines content at the top of the samples.

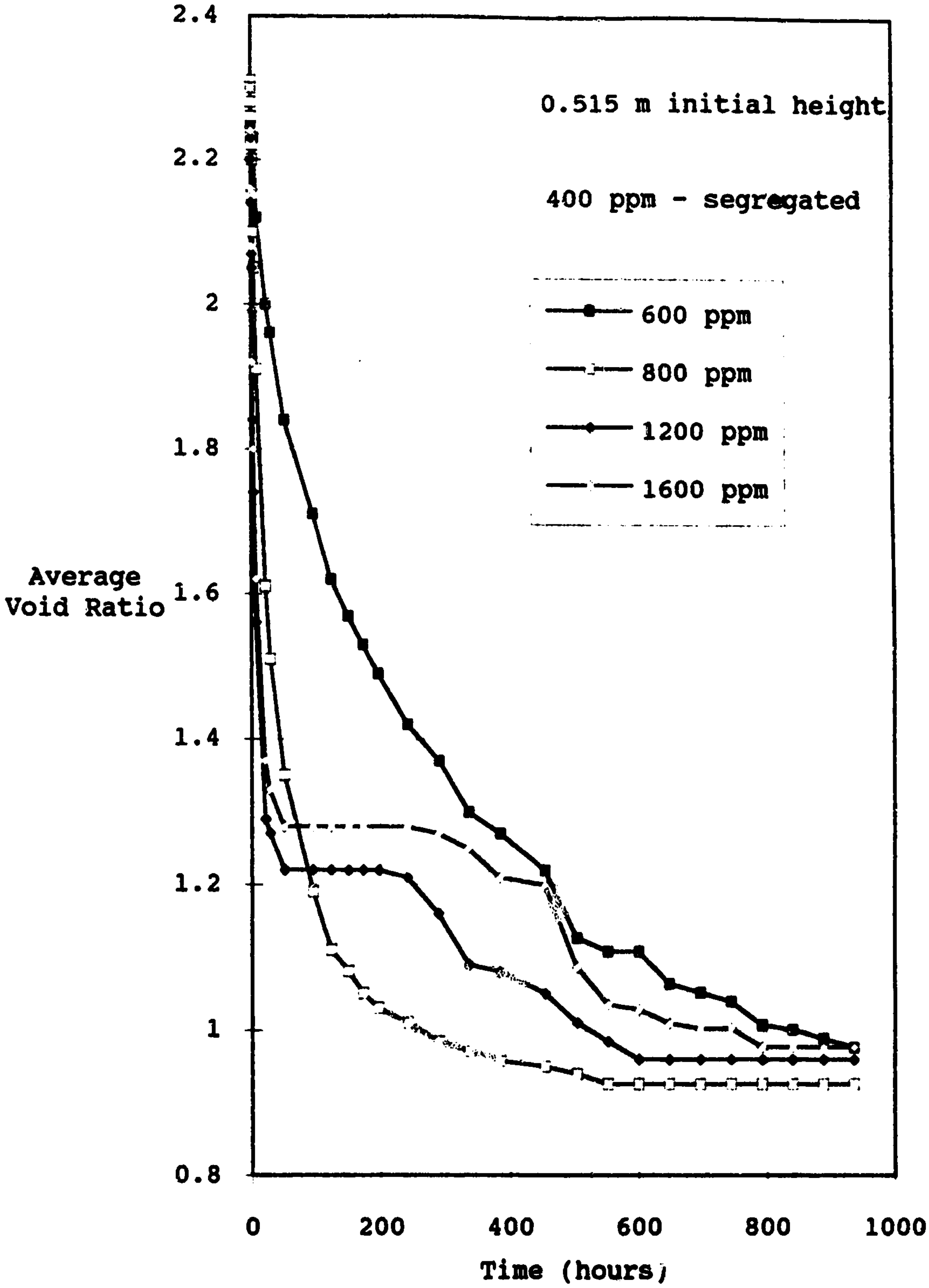


Figure 4.14 Tailings Batch #2 - Variable Lime Content Standpipe Tests

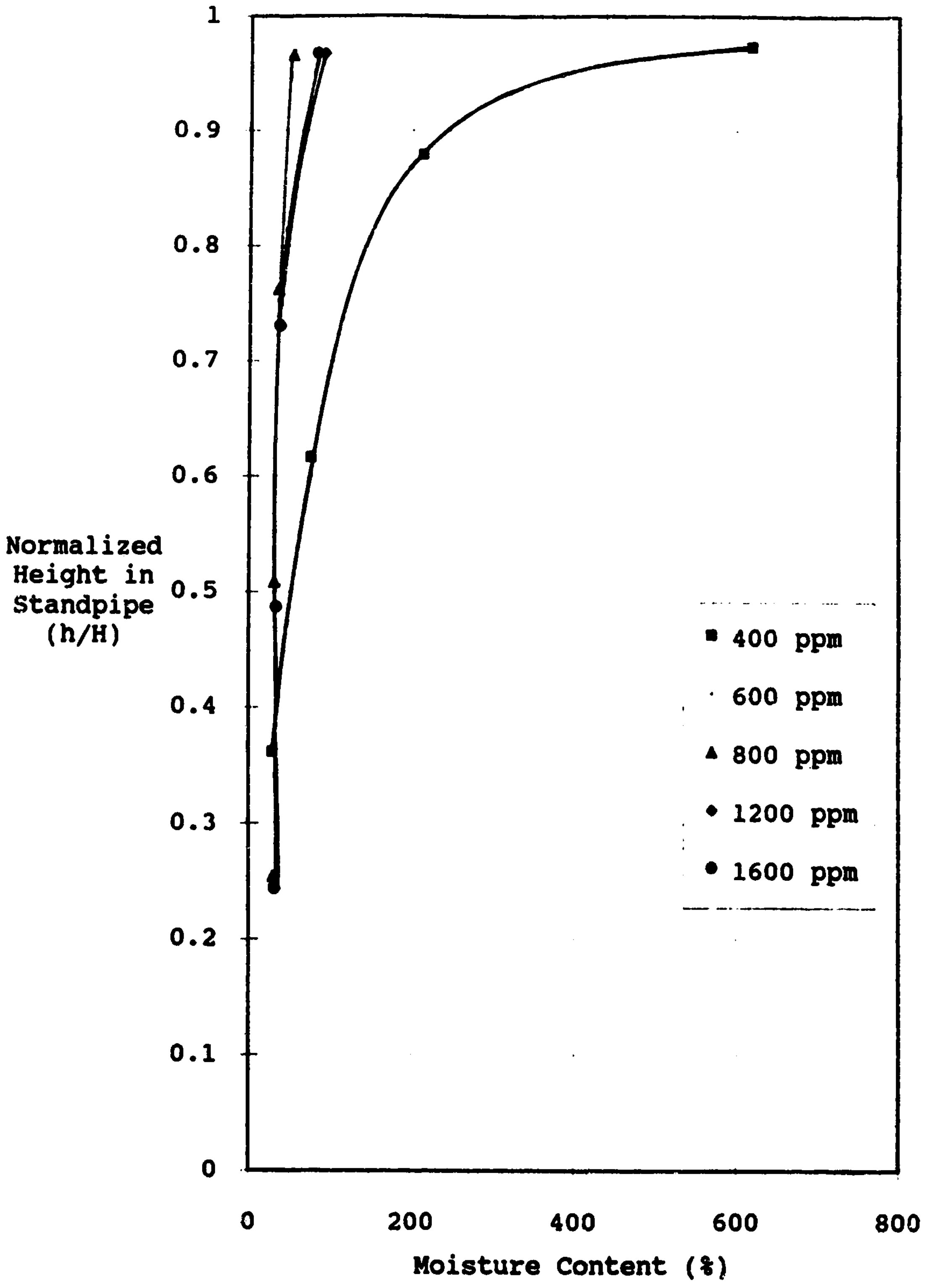


Figure 4.15 Tailings Batch #2 - Moisture Content Profiles After Self-Weight Consolidation - Variable Lime

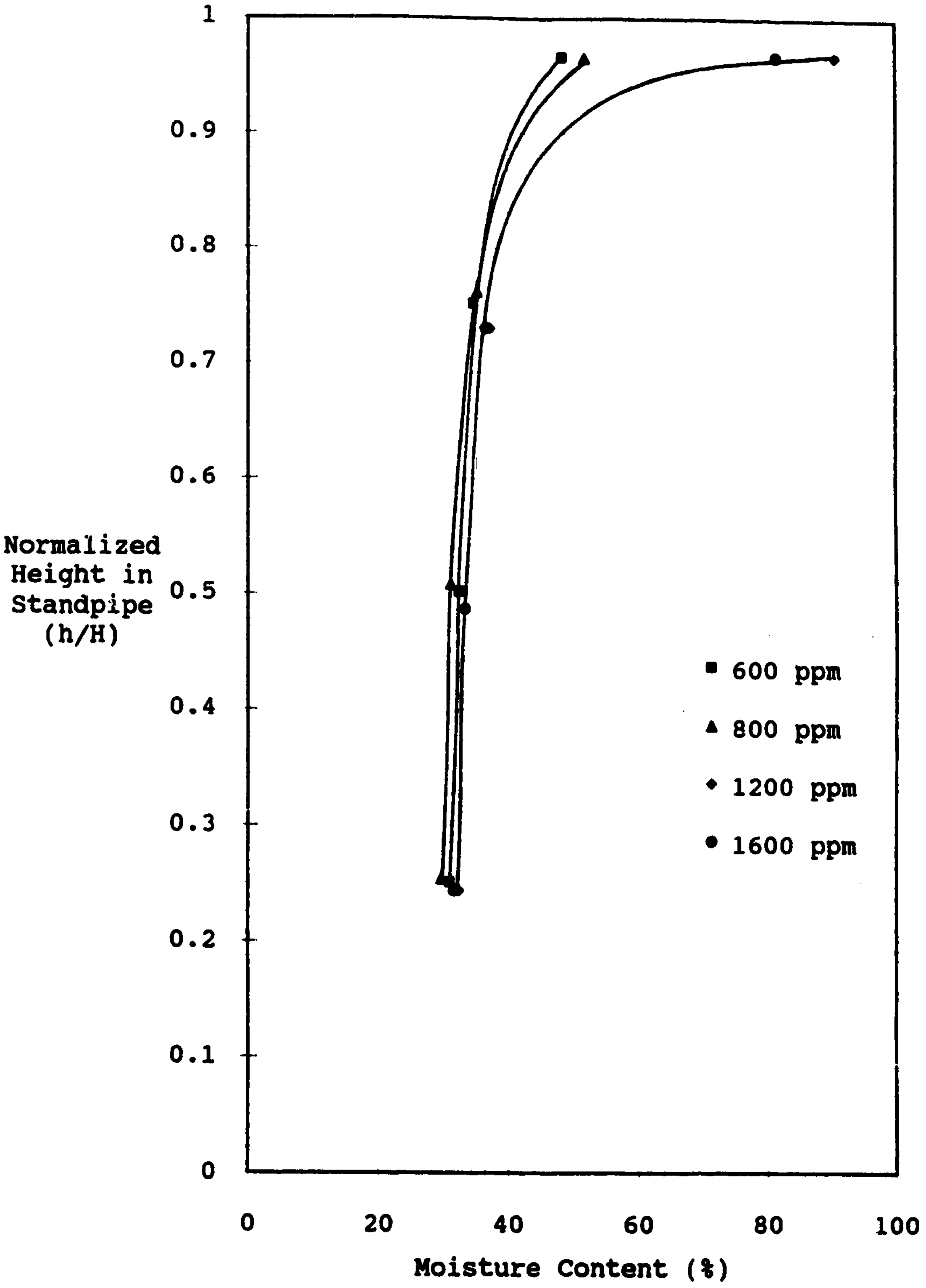


Figure 4.16 Tailings Batch #2 - Moisture Content Profiles

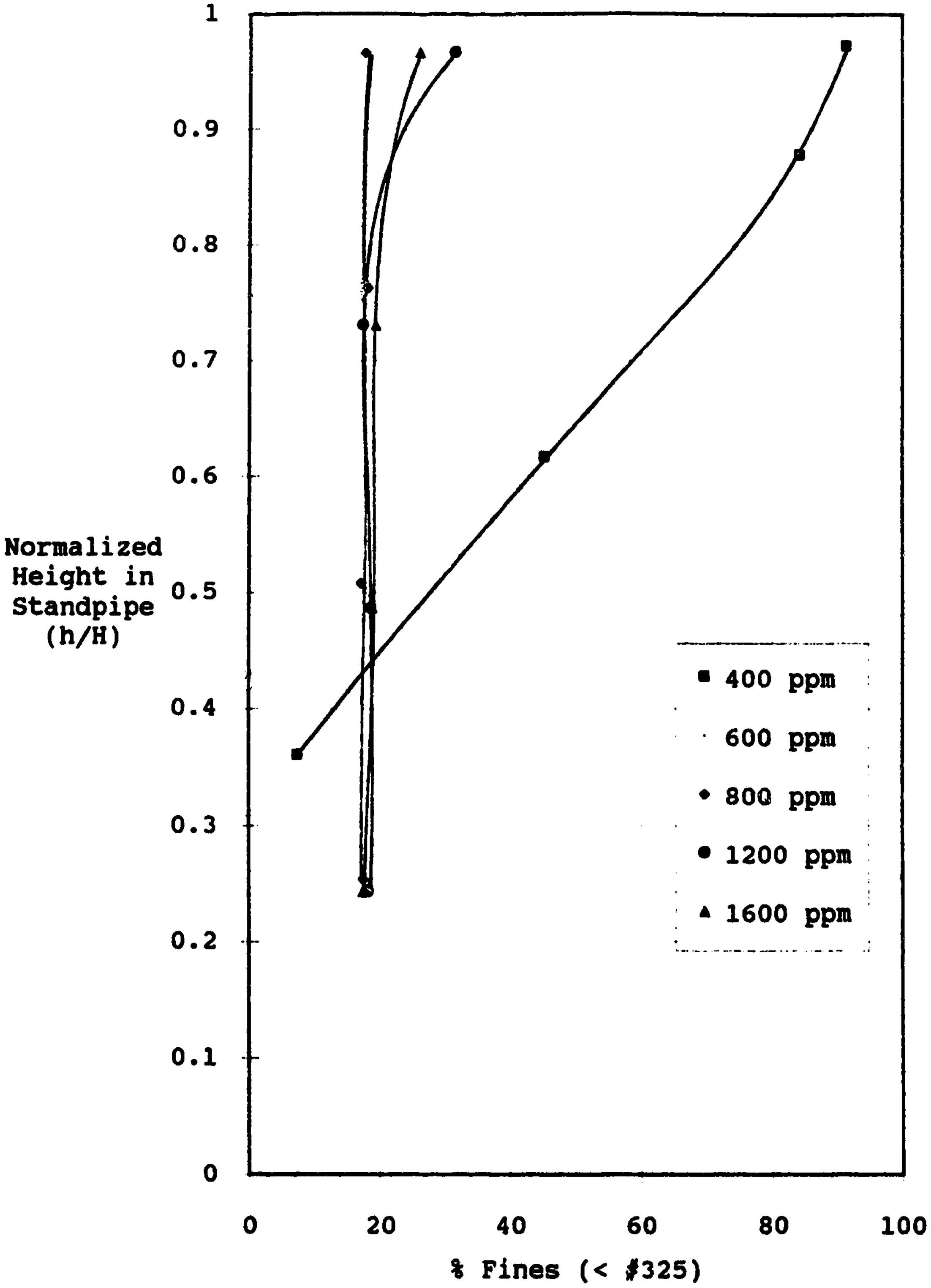


Figure 4.17 Tailings Batch #2 - Fines Content Profiles

1600 ppm tests from batch #2 all end with a similar final average void ratio as opposed to the large range in void ratio of batch #1 tailings. The second is that the second batch of tailings also consolidate to a lower average void ratio than the first batch. These differences are possibly due to the larger self-weight of the second batch due to its higher initial solids content and 10 cm increased thickness of samples (0.515 m vs. 0.415 m). The average effective stress (calculated from the buoyant unit weight of the tailings) of the first batch is 0.7 to 1.0 kPa versus 1.25 kPa for the second batch. The original lime may have also had an affect on the first batch, but as explained earlier this cannot be quantified.

This difference in effective stress may also account for the "collapsing" of the structure causing the 1200 and 1600 ppm samples to further consolidate after it appeared that consolidation was over. This is also seen to some degree in the 800 ppm sample from the first batch.

It was decided that the optimum lime content for these tailings in terms of standpipe tests was in the range of 600 to 800 ppm and all further tests fall within this range. This is approximately 200 ppm higher than the first batch. The difference is likely due to the lime originally added to the first batch by Syncrude and the lower solids content of the first batch

The second set of tests performed on the second batch of tailings were to determine the optimum concentration of A-110 to enhance the consolidation with 800 ppm lime. The results show that the polymer causes the mix to settle and consolidate more rapidly and to a slightly lower void ratio than without A-110 and that 6 ppm appears to be the optimum concentration with 800 ppm lime (Fig. 4.18). The moisture content and fines content profiles (Fig. 4.19 and Figure 4.20) show the three tests to be very similar, with a slight segregation at the top of the samples.

The benefit of A-110 with 800 ppm CaO is not significant in terms of standpipe tests. The polymer may help to reduce segregation due to shearing but that is beyond the scope of this thesis. It may also prove more beneficial at lower lime concentrations, which will be tested in the 1 litre tests described later in the section.

The next standpipe tests performed were three 2m standpipes, one with 800 ppm and two with 600 ppm lime concentrations added. Also included with these tests are four tests performed in the shorter columns from the tailings remaining after the columns were filled. The void ratio - time plot is shown in Figure 4.21.

The 2 m 600 ppm test #1 is not included in the plot as the tailings showed enough segregation that the interface settlement with time could not be measured. The supernatant was too cloudy for a light to penetrate and the surface of the sediment was of too high a water content to feel with a

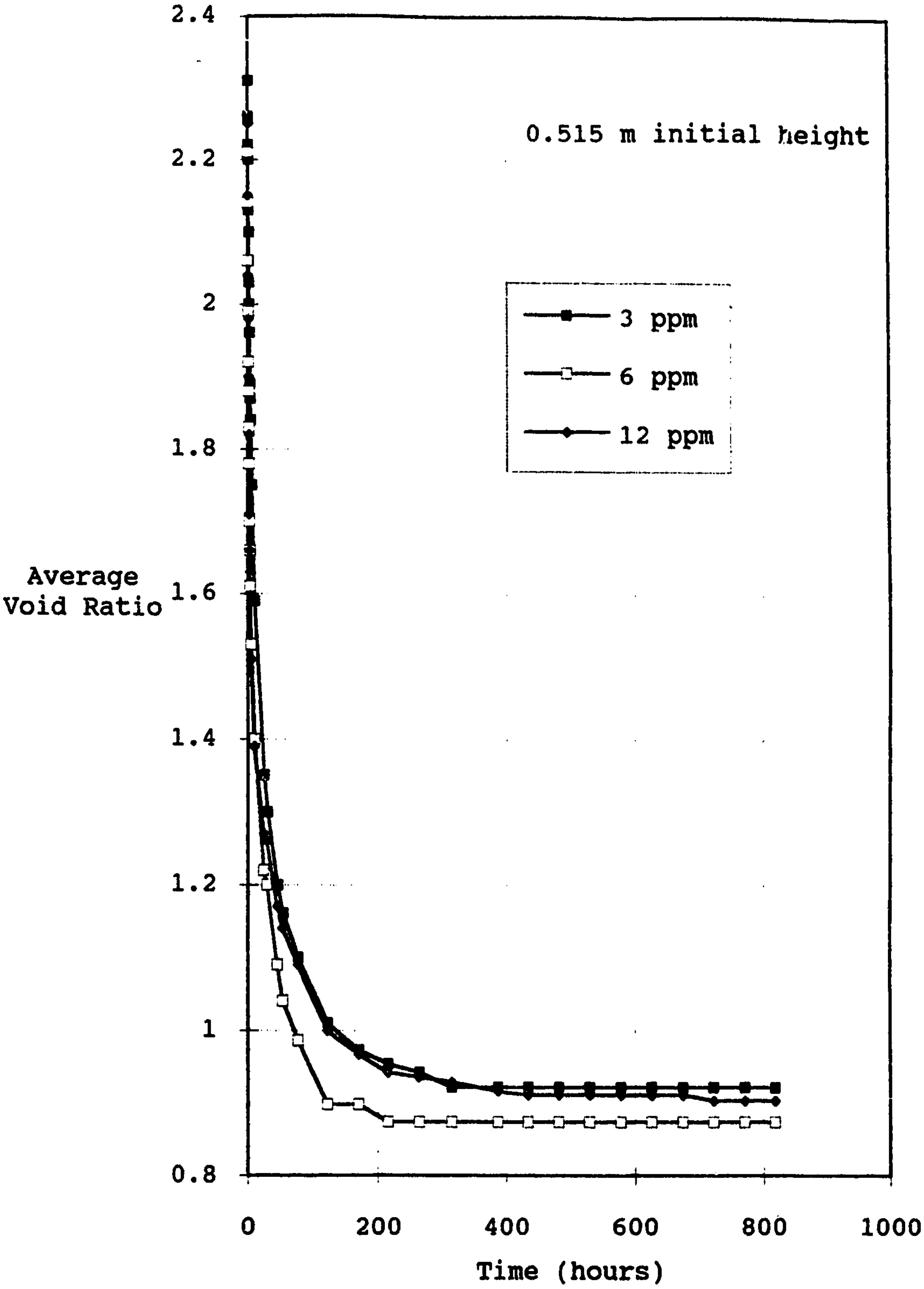


Figure 4.18 Tailings Batch #2 - Standpipe Tests - 800 ppm CaO + A-110

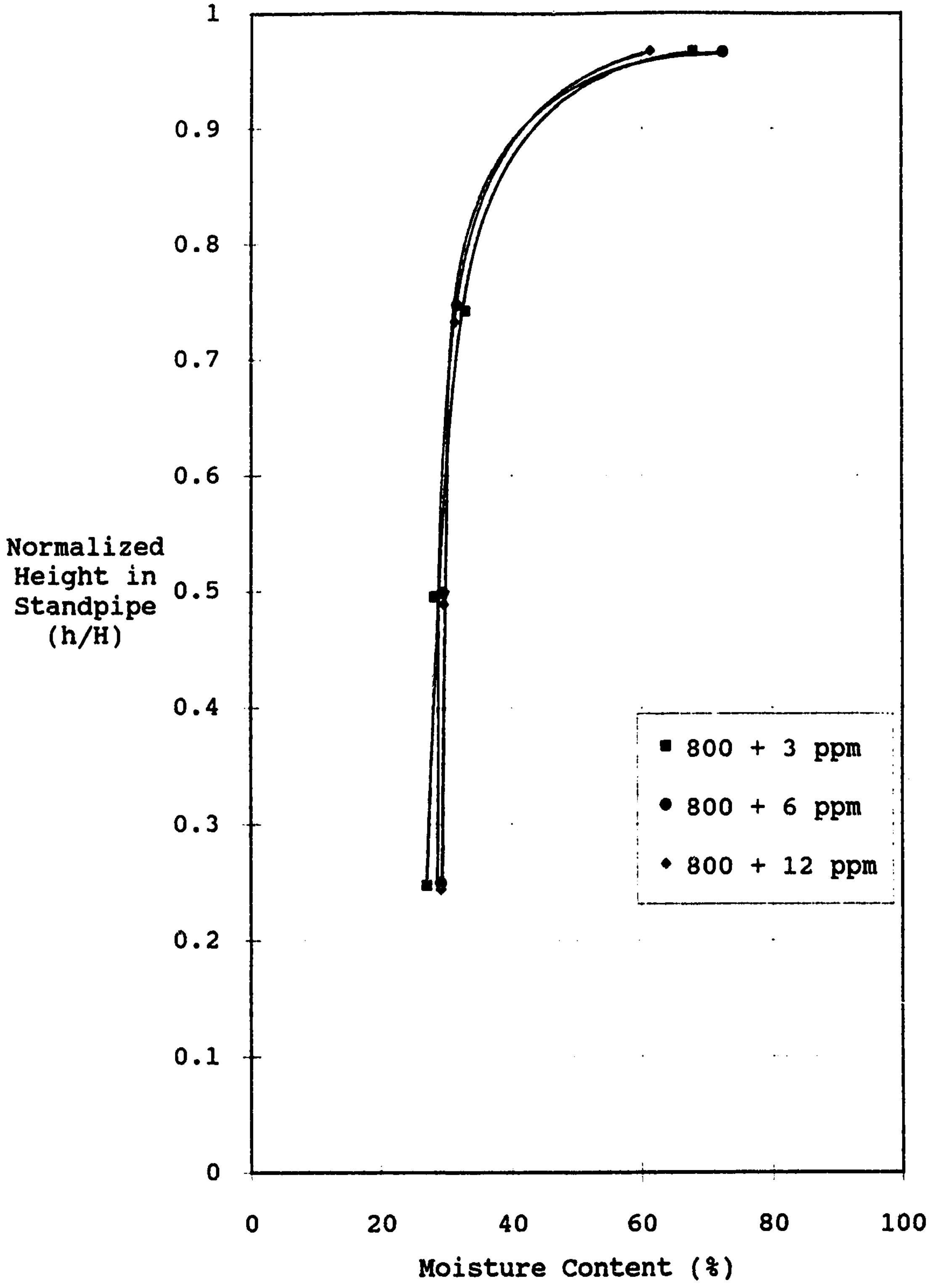


Figure 4.19 Tailings Batch #2 - Moisture Content Profiles After Self-Weight Consolidation - Variable A-110 Standpipe Tests

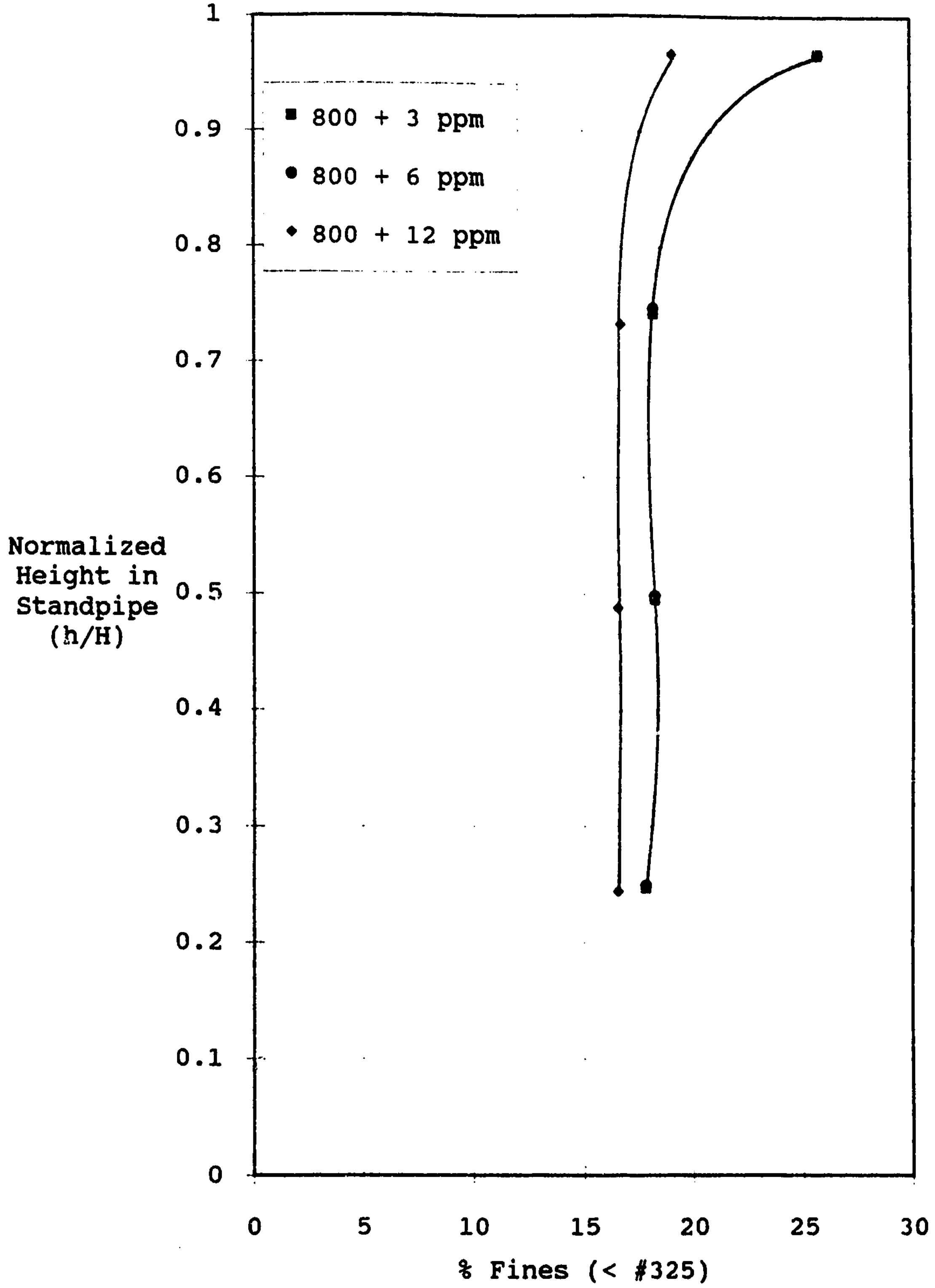


Figure 4.20 Tailings Batch #2 - Fines Content Profiles After Self-Weight Consolidation - Variable A-110 Standpipe Tests

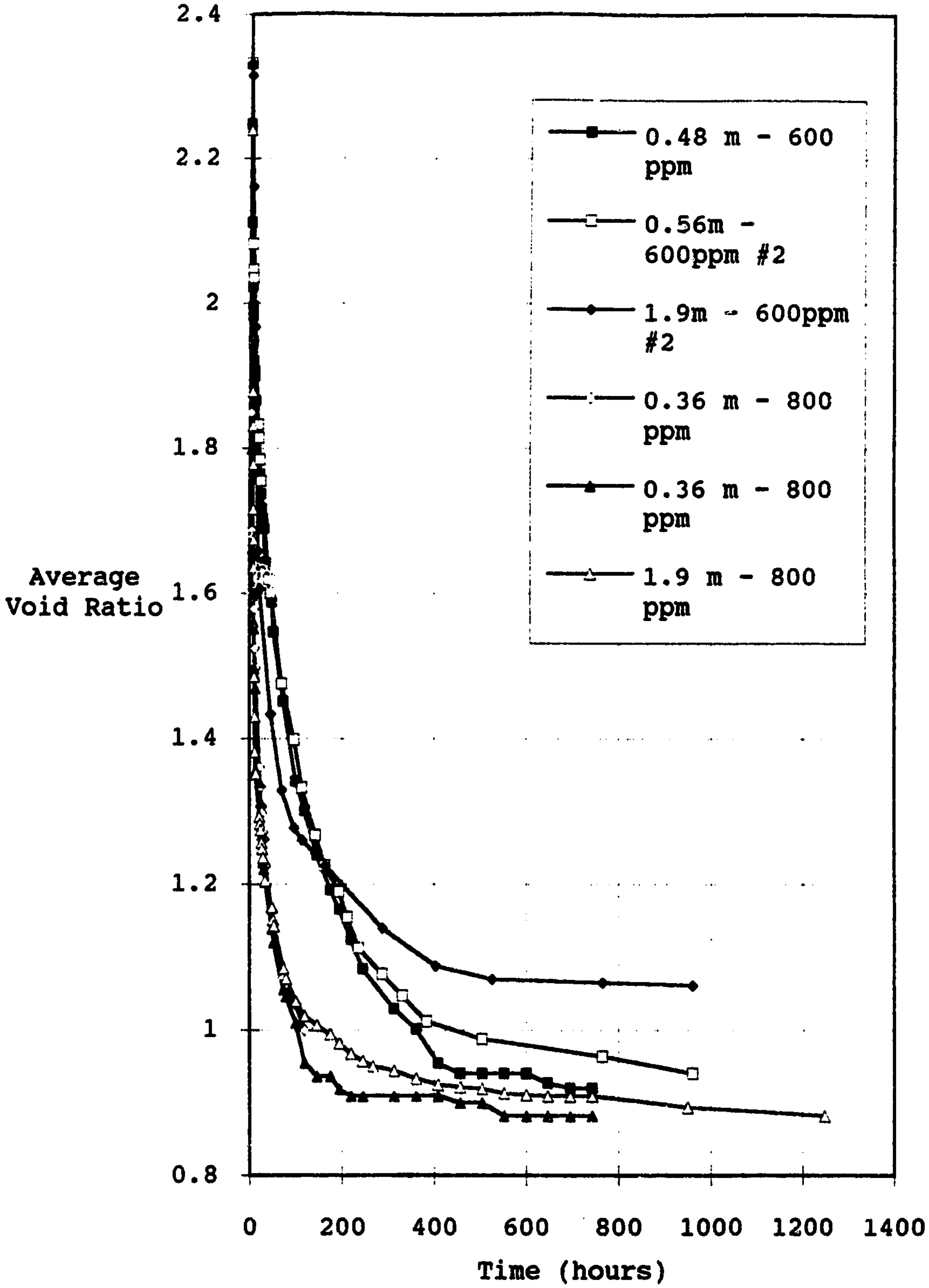


Figure 4.21 Tailings Batch #2 - Standpipe Tests - (2 m vs 0.5 m standpipes)

probe. The fines content profile (Fig. 4.23) and the water content profile (Fig. 4.22) both show the high fines, thin solids content zone on top of the sample. It is noted that the water and fines contents for the bottom zone are likely too high as the sampling technique tended to draw off the water before the sand. The pore pressure plots (Fig 4.24 and 4.25) also show a rapid decrease of pore pressure with time as the sediment would have a higher permeability than if the fines were equally distributed. The permeability at the top would be higher because of the high water content here. The permeability at the bottom would be higher due to the lower fines content here. The problem with this is that once another layer was placed over this one, the fines would run away or form a low permeability zone upon consolidation, with little shear strength. The pore pressure plots for the 800 ppm test (Fig. 4.26 and 4.27) show a much more gradual decrease of the pore pressure with time as the consolidation proceeded and the permeability decreased.

The reason for the segregation of the 600 ppm standpipe is likely due to the tailings being poured into the standpipe, possibly with enough energy (or air entrapment) to cause segregation. Both standpipes also showed a 4 - 5 cm layer of foam on the surface due to air coming out of the sample. It is believed that this air was due to the pouring process and not the mixing process as no foam occurred on the shorter standpipes from the same barrel. This foam occurred for the first three to four hours until all the air

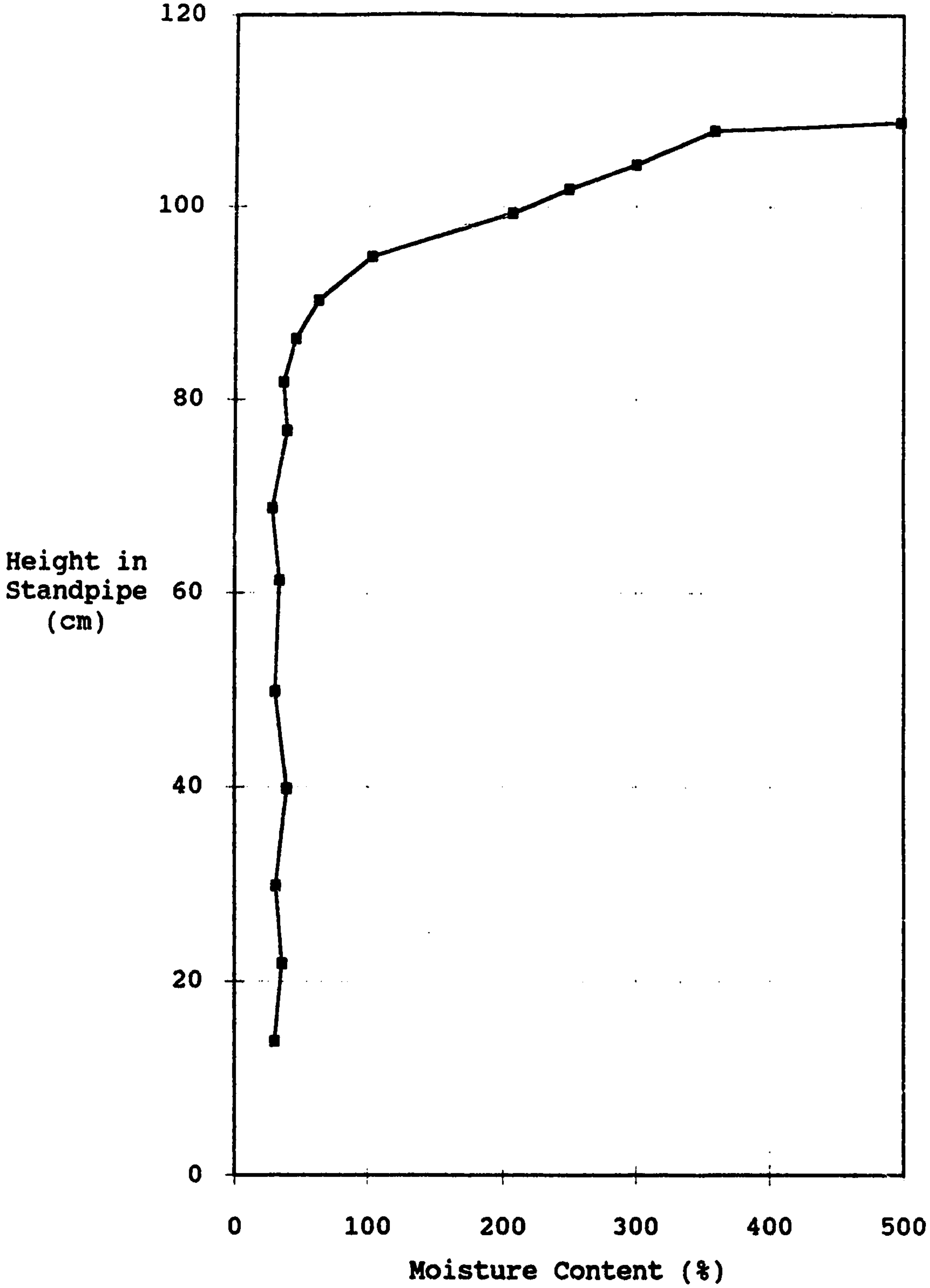


Figure 4.22 Tailings Batch #2 - Moisture Content Profile After Self-Weight Consolidation - 600 ppm 2 m Standpipe #1

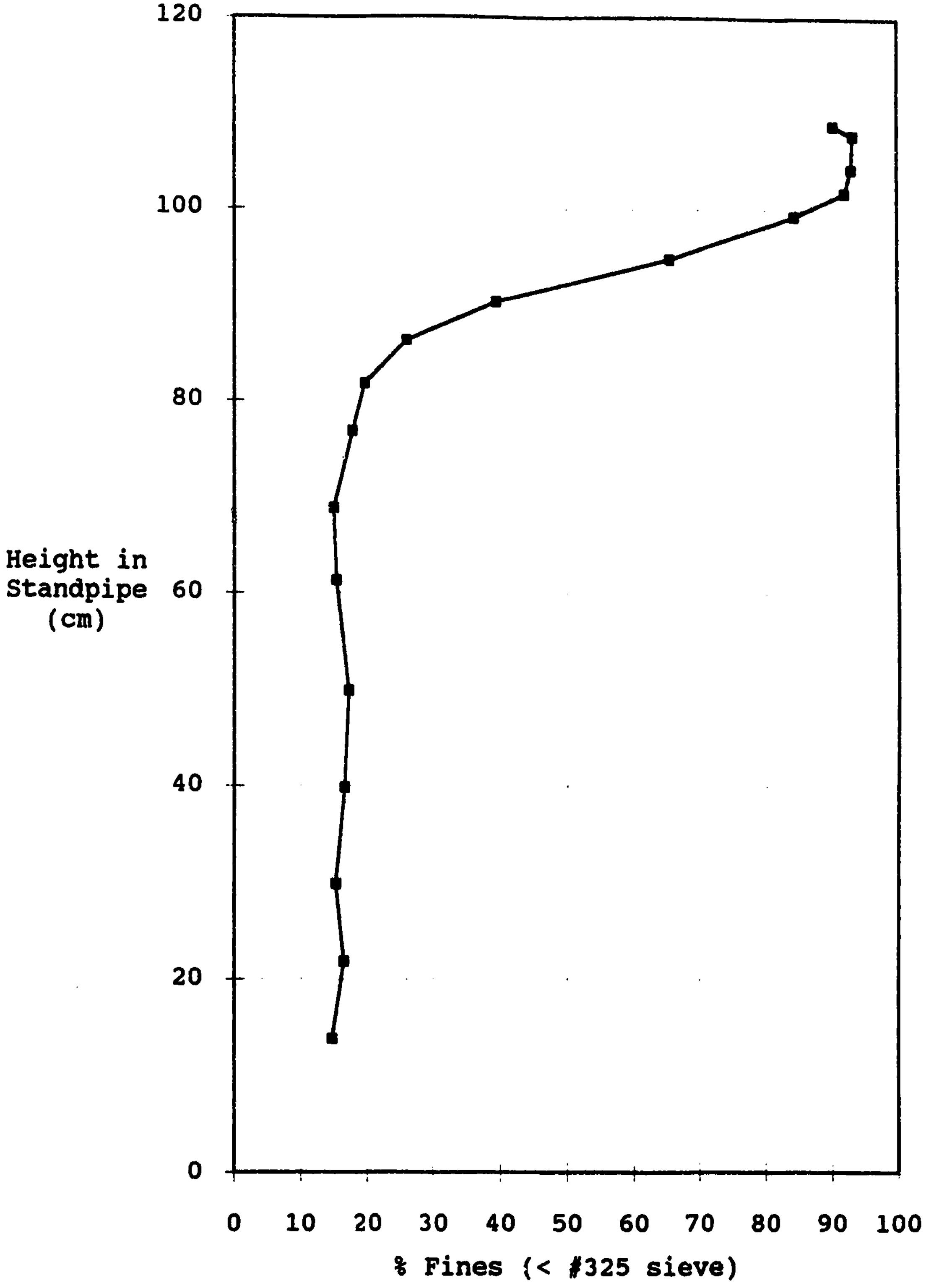


Figure 4.23 Tailings Batch #2 - Fines Content Profile After Self-Weight Consolidation - 600 ppm 2 m Standpipe #1

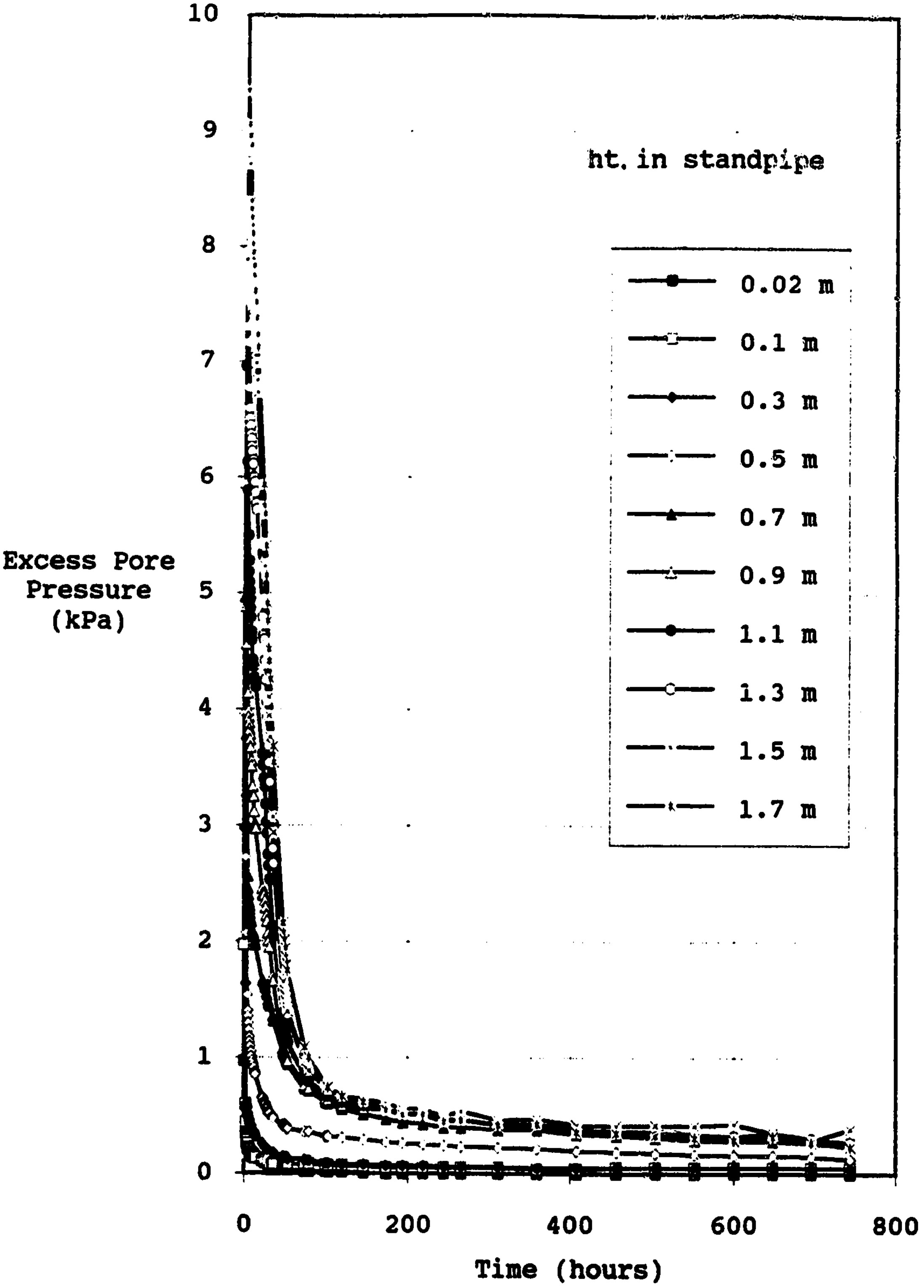


Figure 4.24 Tailings Batch #2 - 2m Standpipe Manometer Readings - 600 ppm #1

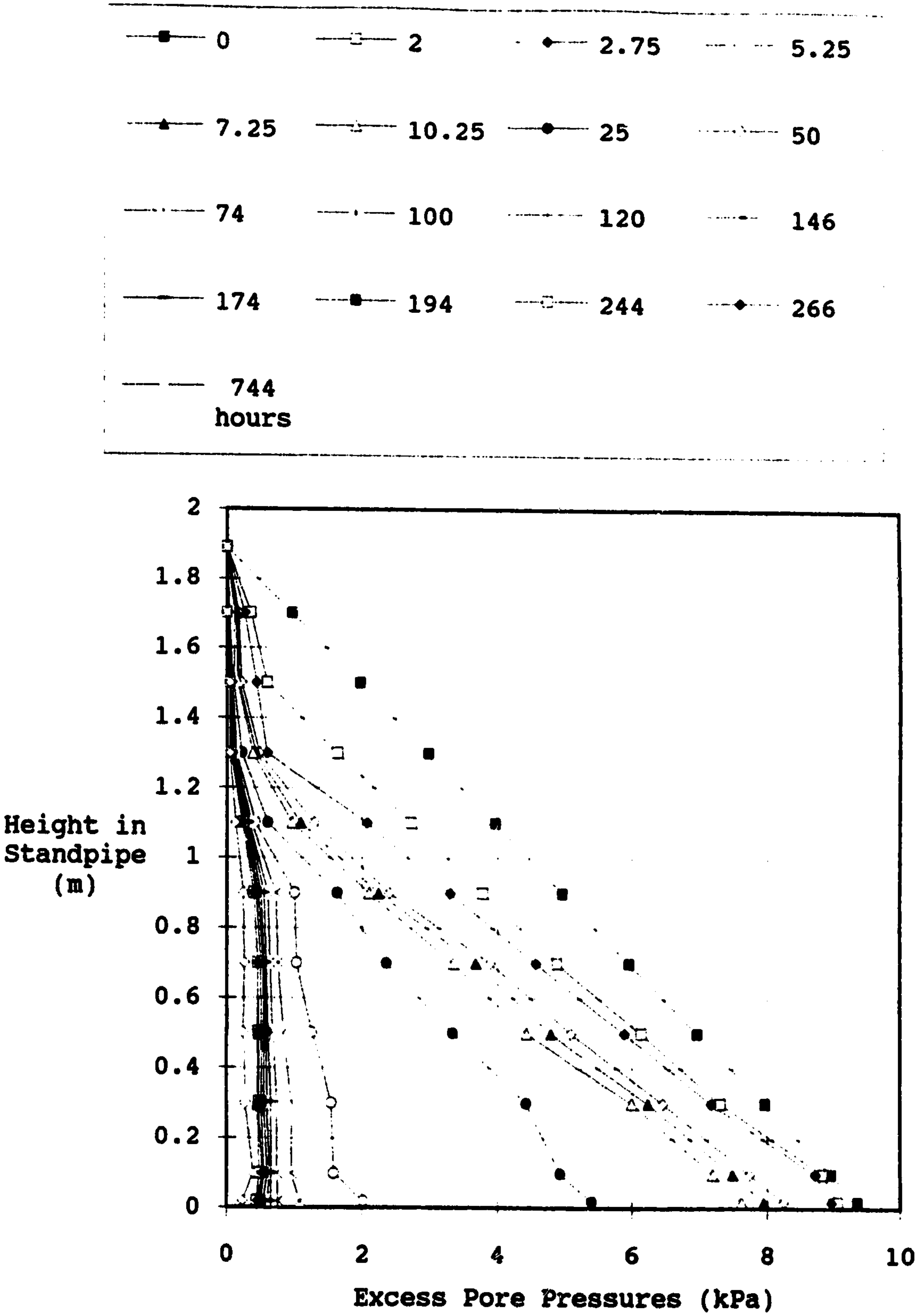


Figure 4.25 Tailings Batch #2 - Pore Pressure Profiles for 2 m Column (600 ppm #1)

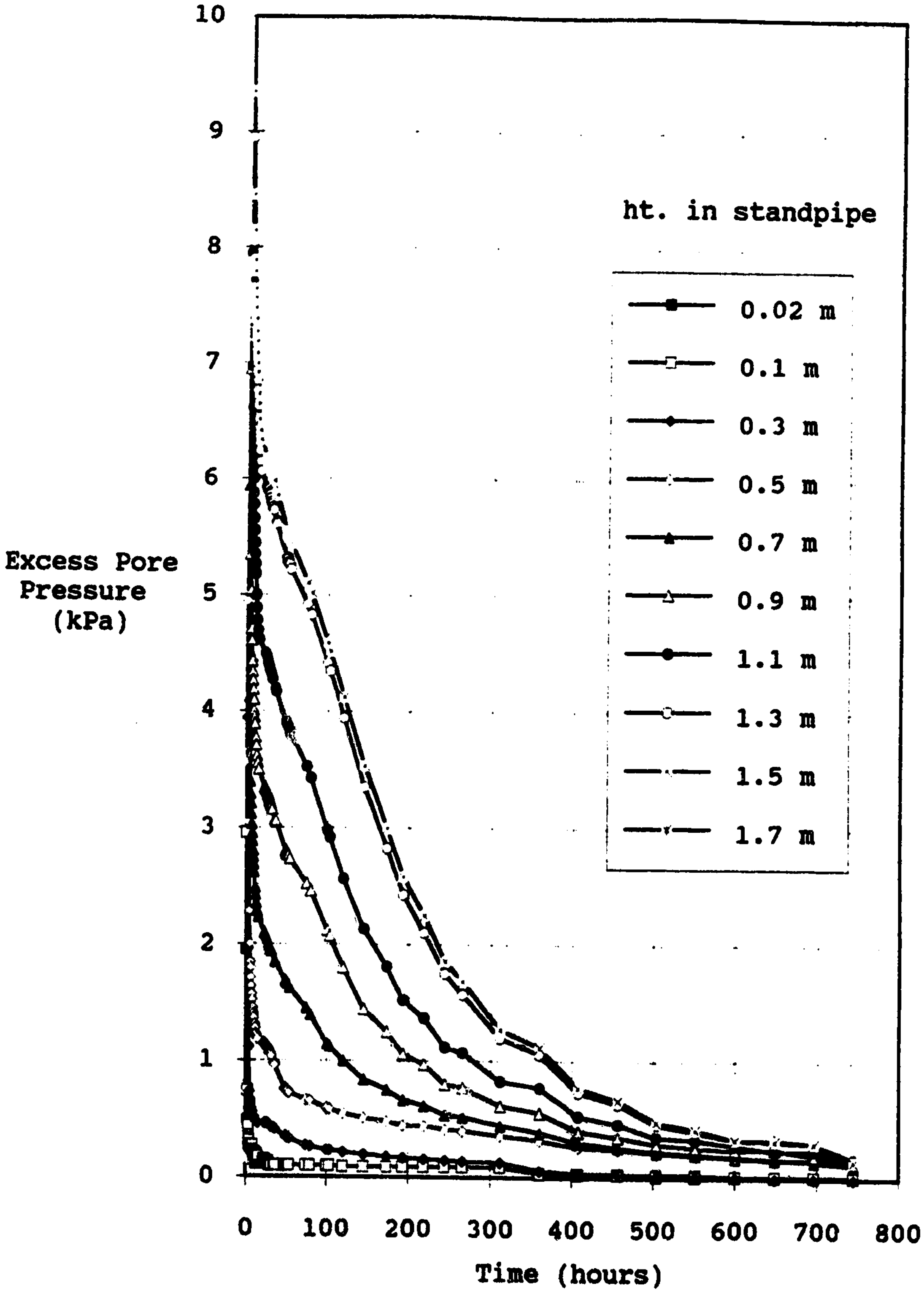


Figure 4.26 Tailings Batch #2 - 2m Standpipe Manometer Readings - 800 ppm

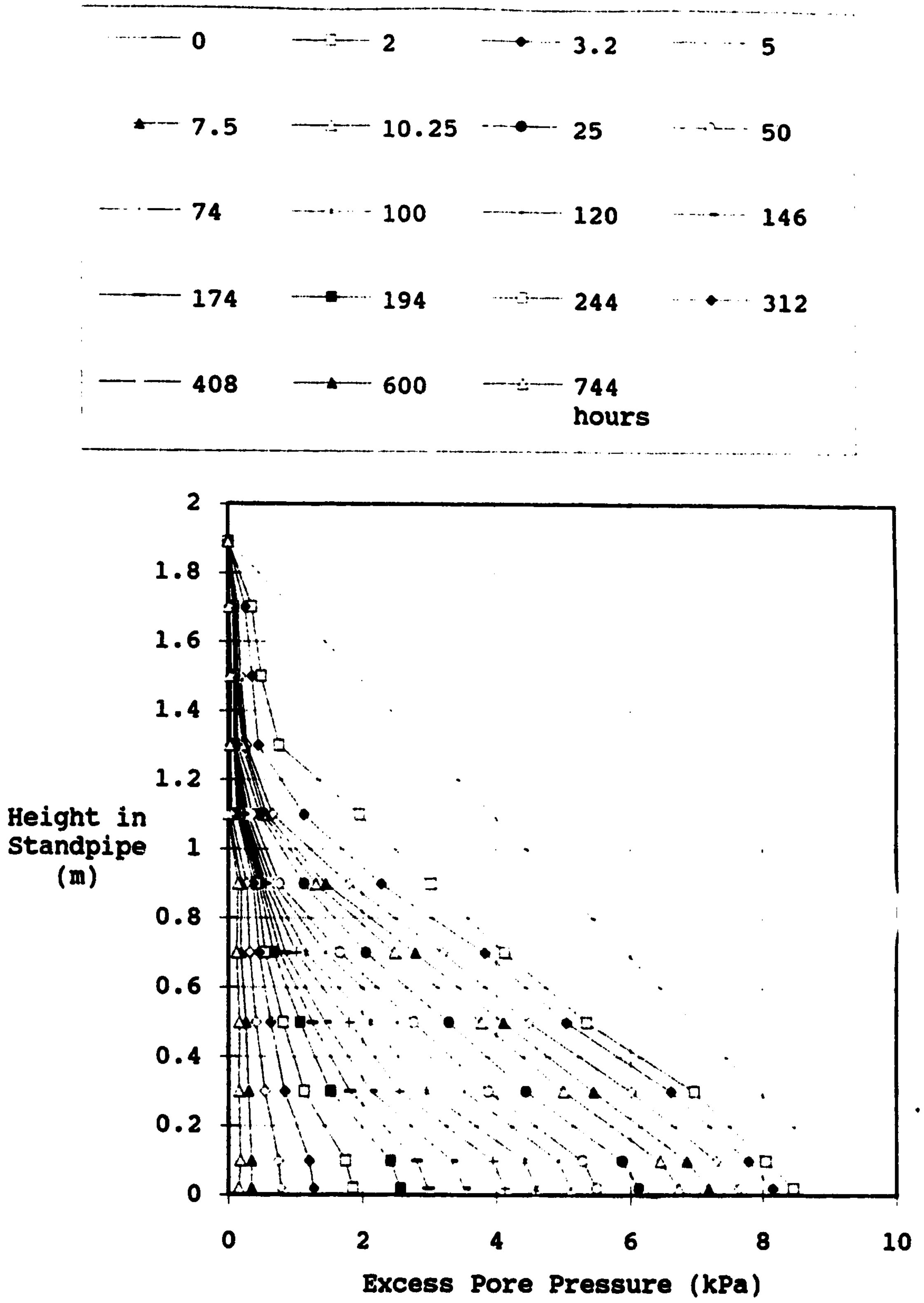


Figure 4.27 Tailings Batch #2 - Pore Pressure Profiles for 2 m Column (800 ppm)

had come out of the samples. This foam then had to be skimmed off the surface to allow the interface height to be measured.

A second 600 ppm 2 m standpipe was then performed, this time attempting to place the tailings in the column with less air entrapment. This was achieved with a pail with a stopper in the bottom as shown in Figure 4.28. The tailings were deposited in lifts by lowering the pail to the surface and pulling the stopper out. The test still showed air coming out of the sample, but not as much as the first test. The supernatant was also cloudy although not as much and the interface surface often had to be deduced from the distance that the tape went to cause sediment to be stirred up. This test also appears to have partially segregated as the pore pressures behaved similarly to the first test (Fig. 4.29 and 4.30). This test also shows a higher settled void ratio than the other tests, indicating the low solids content zone on top of the sample. The two 0.5 m 600 ppm tests from the same material as the 2 m standpipes did not segregate, indicating that the 600 ppm concentration is very close to the boundary of segregating and non-segregating mixes in terms of gentle deposition.

It is also very interesting to note that the 2 m 800 ppm test settled very quickly during the hindered settling and beginning of self-weight consolidation stages (as fast as the 0.36 m test). It was expected that the 2 m test

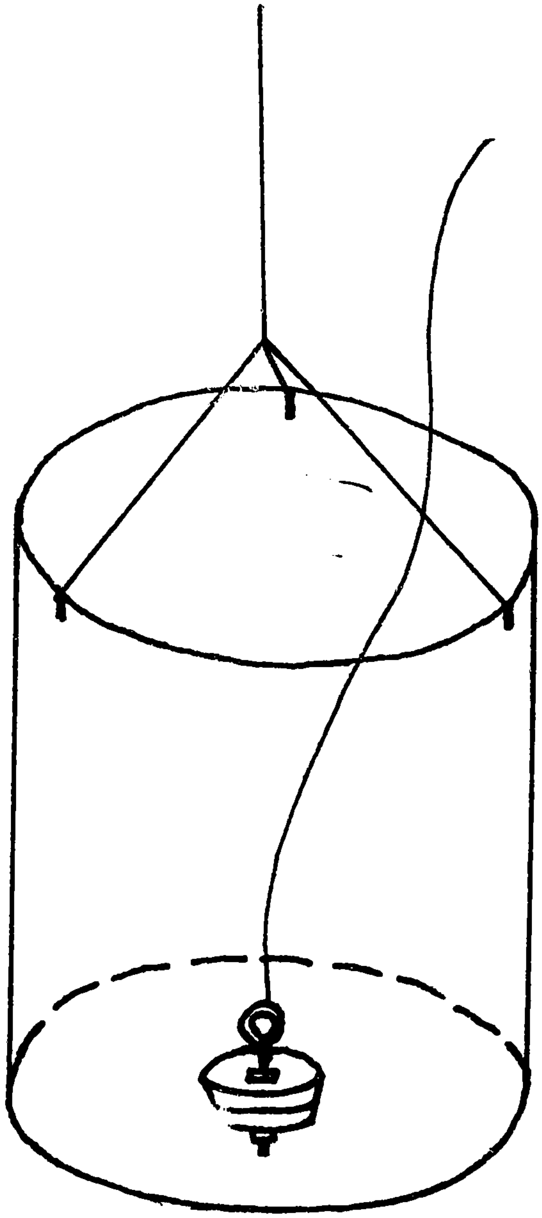


Figure 4.28 Pail with Stopper for 2 m Standpipe Tests

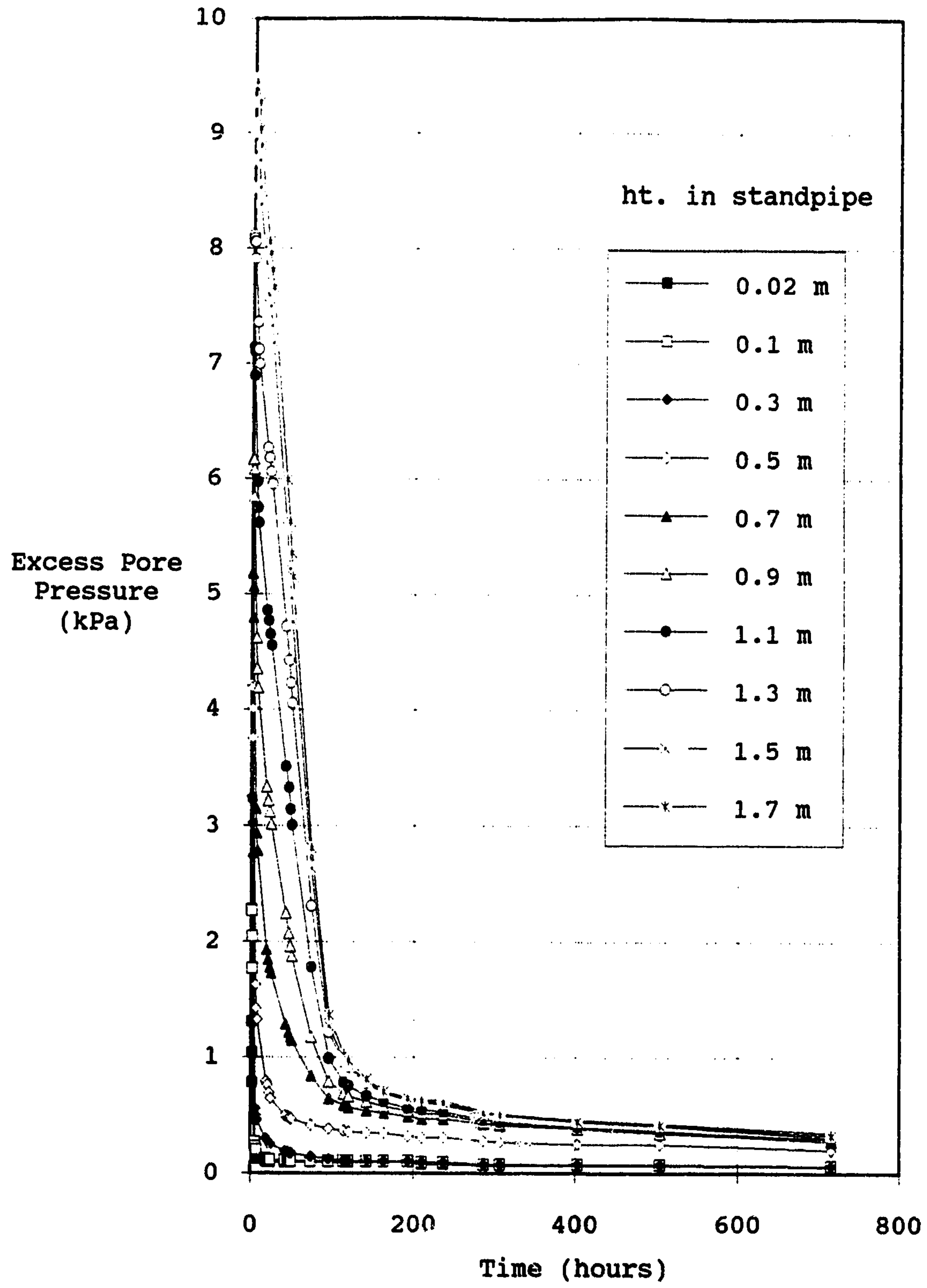


Figure 4.29 Tailings Batch #2 - 2m Standpipe Manometer

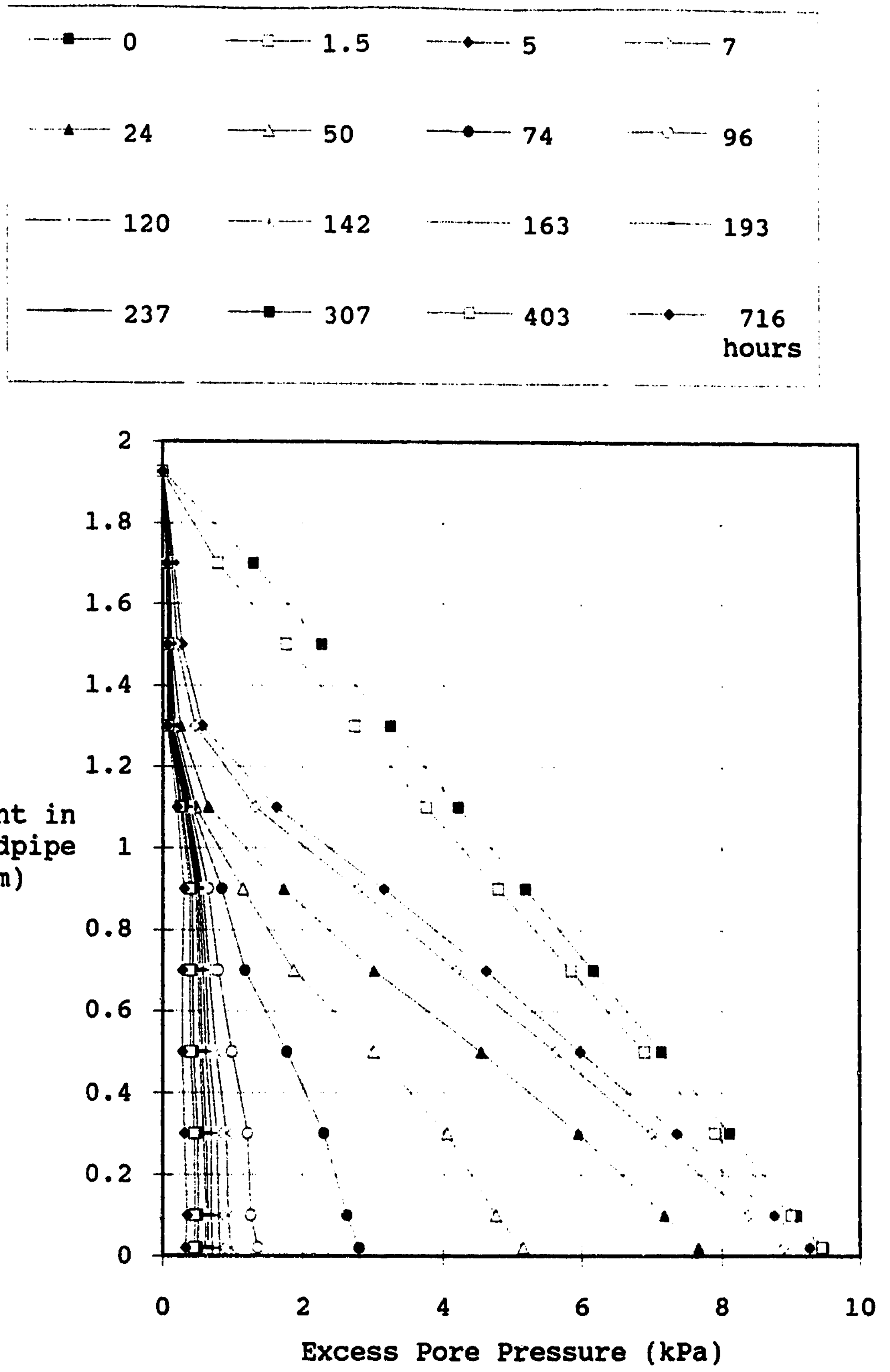


Figure 4.30 Tailings Batch #2 - Pore Pressure Profiles for

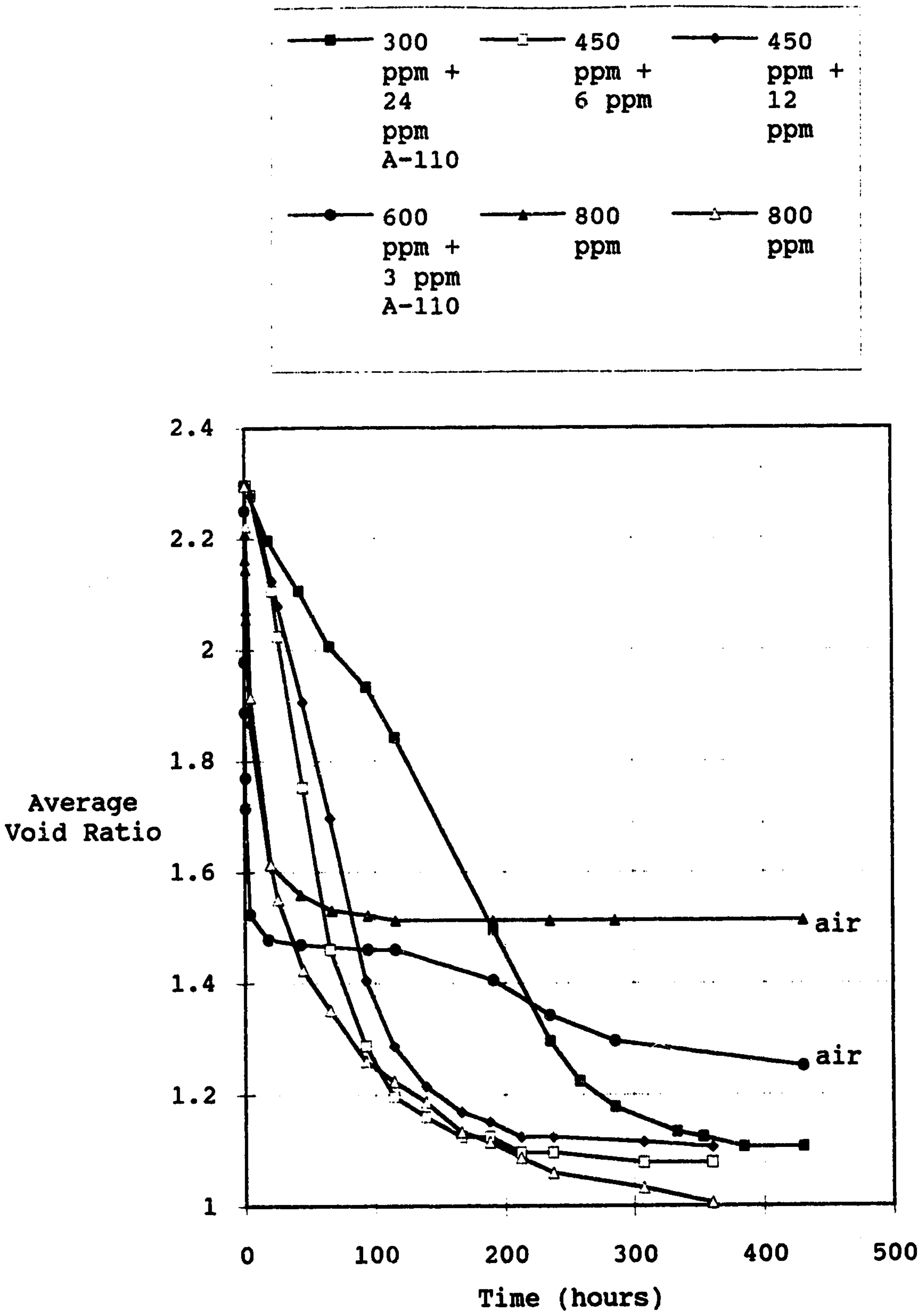
would take five times longer to settle to the same void ratio as the 0.36 m test since it is five times higher. The results indicate that the permeability of the 2 m test was significantly higher than the shorter test. This difference in permeability is possibly due to channeling through the sample which may be associated with the air coming out of the sample. Channeling is quite common in batch thickening experiments and often results in quite substantial increases in permeability (Jones, 1985).

Also, the 600 ppm tests in the shorter columns from auger mixing settle much faster than the 600 ppm test using the blade mixer, likely due to the better mixing achieved with the auger. The auger mixing showed immediate results from the addition of lime, with the viscosity of the mixture increasing such that it looked like chocolate pudding. The 600 ppm tests still settled more slowly than the 800 ppm tests, though.

Several 1 litre tests were performed to further investigate the use of A-110 with lime and to determine if sulphuric acid could be used to obtain non-segregating mixes. A summary of the tests is shown in Table 4.1. A plot of void ratio versus time of selected lime and lime with polymer tests is shown in Figure 4.31. The two tests marked air on the plot are tests where the mixing process had trapped considerable air in the tailings and shows, at

Table 4.1 Tailings Batch #2 - 1 Litre Tests

Test	CaO	A-110	Initial	Final	Duration	Comments
	(ppm)	(ppm)	Void	Void	(hours)	
			Ratio	Ratio		
1	-	-	-	segreg.	-	control
2	-	6	-	segreg.	-	
3	-	12	-	segreg.	-	
4	-	24	-	segreg.	-	
5	300	3	-	segreg.	-	
6	300	6	-	segreg.	-	
7	300	12	-	segreg.	-	
8	300	24	2.3	1.11	430	
9	450	6	2.3	1.08	360	
10	450	12	2.3	1.11	360	
11	600	3	2.3	1.25	430	air
12	600	6	2.3	1.32	430	air
13	600	12	2.3	1.27	430	air
14	800	-	2.3	1.51	430	air
15	800	-	2.3	1.01	360	
	H_2SO_4 (ml/l)					
16	3	-	-	segreg.	-	
17	5	-	2.3	1.71	740	
18	7.5	-	2.3	1.25	740	
19	7.5	-	2.31	1.3	408	
20	10.5	-	2.3	1.31	740	
21	10.5	-	2.3	1.25	360	
22	10.5	-	2.35	1.25	408	
23	10.5	-	2.36	1.44	408	
24	15	-	2.26	1.31	408	
25	17.5	-	2.44	1.54	408	

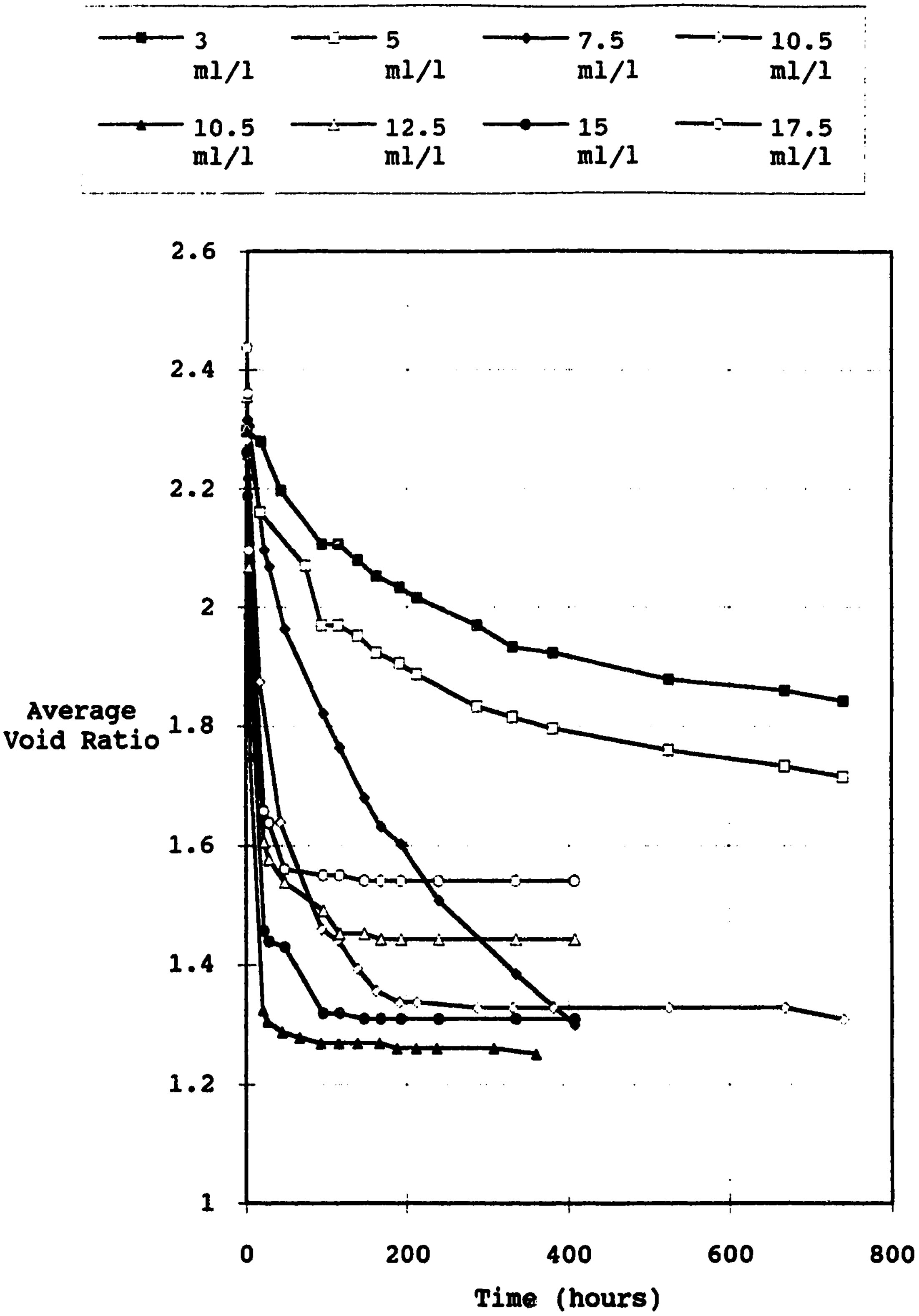

300 ppm + 24 ppm A-110
450 ppm + 6 ppm
450 ppm + 12 ppm
600 ppm + 3 ppm A-110
800 ppm
800 ppm
2.4
2.2
2
1.8
1.6
1.4
1.2
1
Average Void Ratio
air
air
0
100
200
300
400
500
Time (hours)

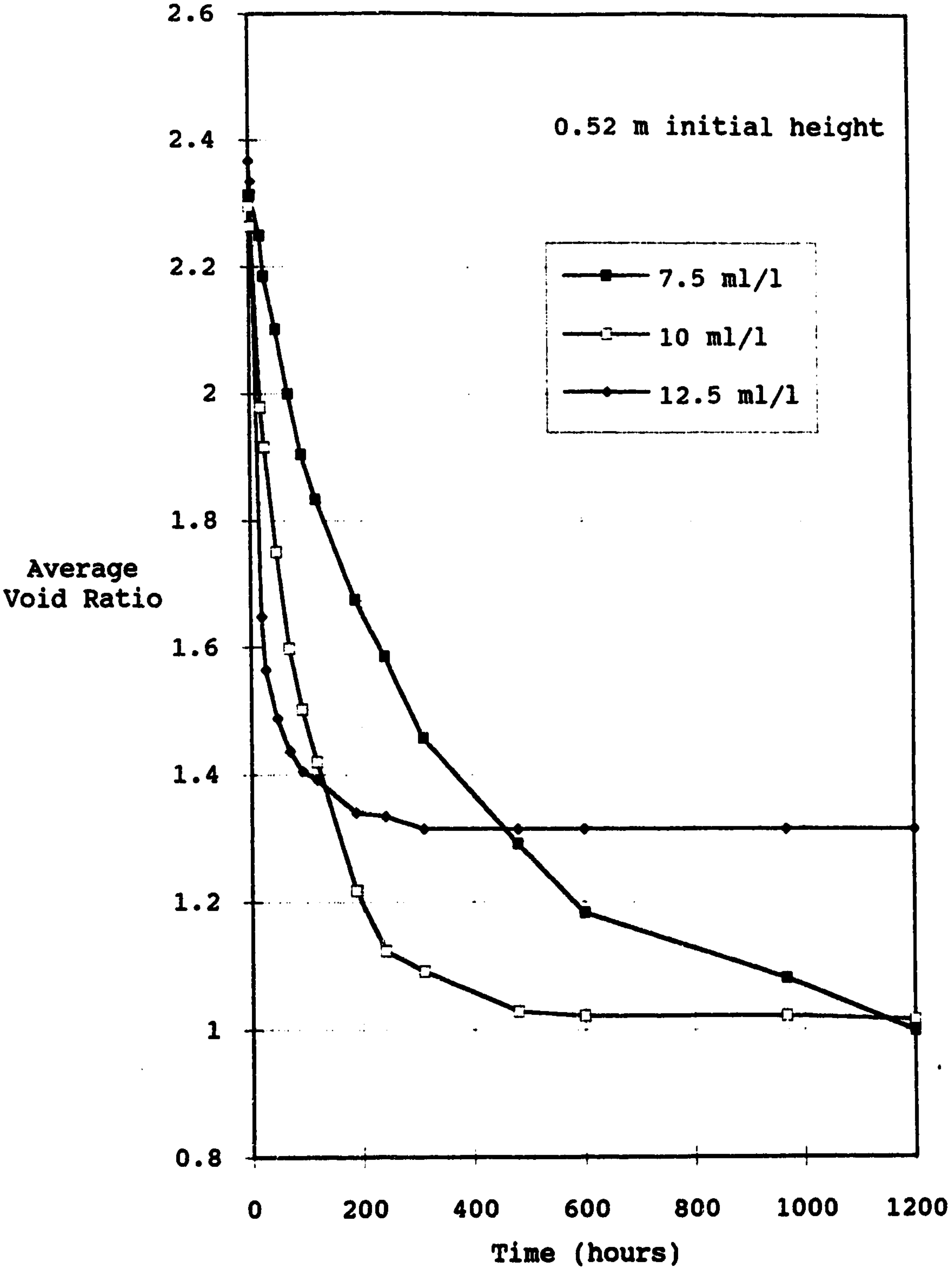
serves to hinder the self-weight consolidation of the sample.

The polymer results show that with 300 ppm lime, approximately 24 ppm A-110 is required before the mix is non-segregating. With 450 ppm lime, 6 ppm A-110 was sufficient to stop segregation. The polymer tests settle to a higher void ratio than tests in the larger cylinders, which may be due to the small diameter of the glass cylinders or the mixing process. It was found to be more difficult to mix the smaller samples without entraining air.

Figure 4.32 shows the results of some 1 litre tests using sulphuric acid. The concentration of acid used is in terms of ml of 10% H_2SO_4 to litres of total volume of tailings. The same problems of air entrapment discussed above also occurred here. Non-segregating mixes of tailings can be achieved, but the settled void ratio appears to be somewhat higher than for lime flocculated tailings. A range of 7.5 ml/l to 12.5 ml/l was chosen as an optimum range for further larger scale tests in the PVC standpipes.

Three 0.5 m standpipe tests with sulphuric acid are shown in Figure 4.33. Concentrations of 10% acid of 7.5, 10, and 12.5 ml/l were used. The plot shows that the 7.5 and 10 ml/l tests behaved very similarly to the 600 and 800 ppm CaO tests in Figure 4.14, respectively, although the acid tests do settle a little more slowly. This indicates

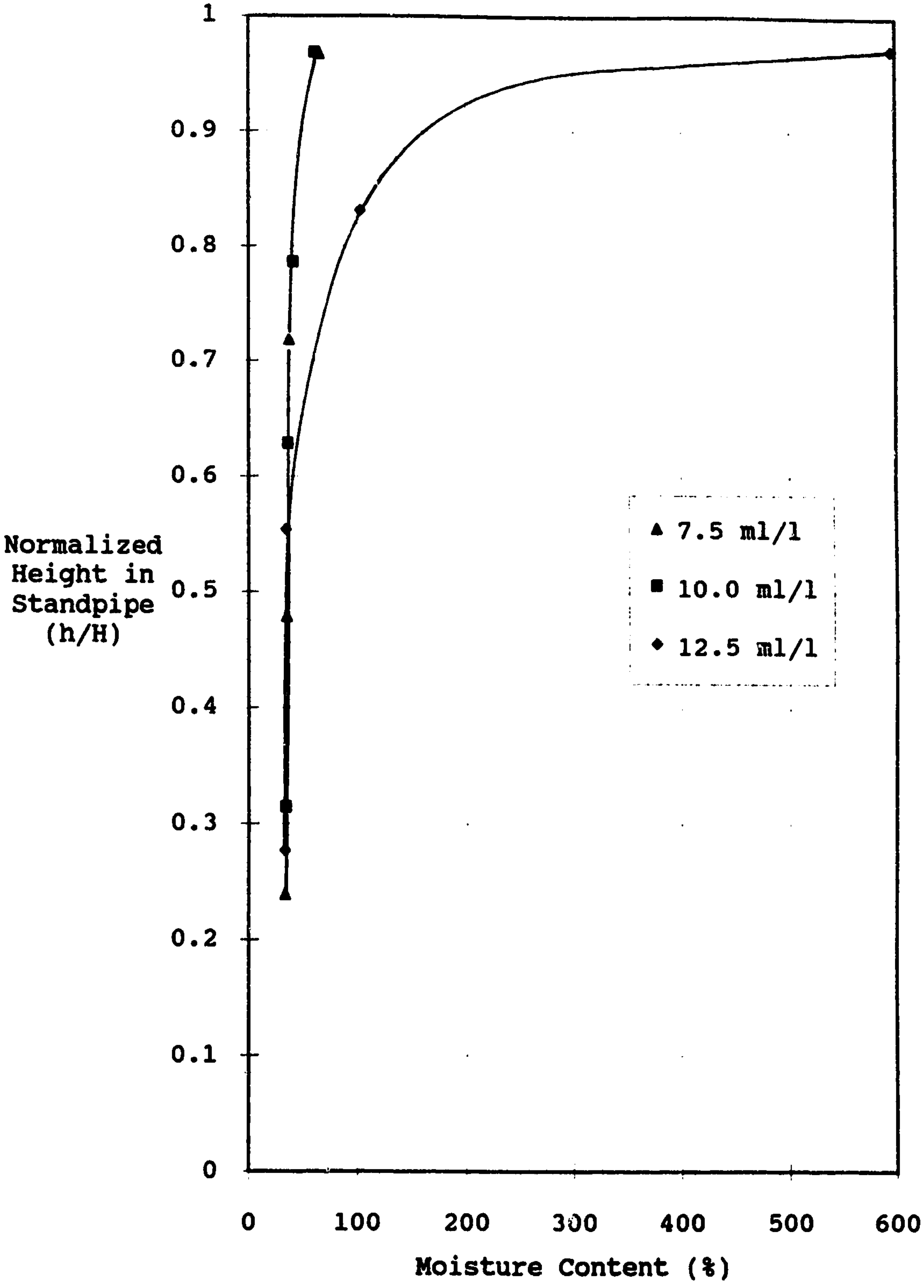

3 ml/l
5 ml/l
7.5 ml/l
10.5 ml/l
10.5 ml/l
12.5 ml/l
15 ml/l
17.5 ml/l
Average Void Ratio
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0
200
400
600
800
Time (hours)

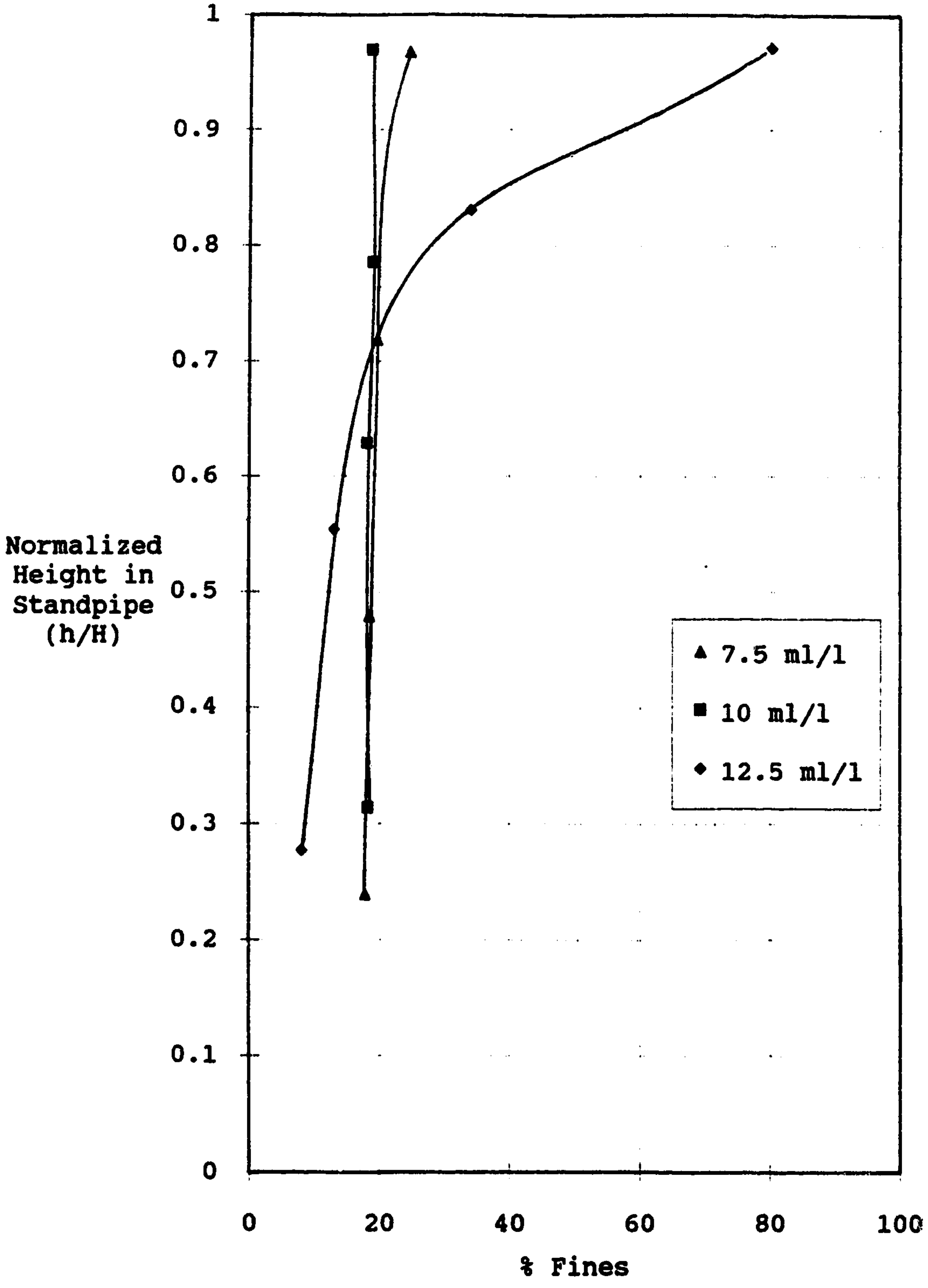

0.52 m initial height
7.5 ml/l
10 ml/l
12.5 ml/l
Average Void Ratio
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0
200
400
600
800
1000
1200
Time (hours)

acid tests is that the acid tends to break the emulsion formed by NaOH and bitumen in the tailings as indicated in the patent by Behan and Vendrinsky (1976). This results in a considerable amount of bitumen and froth on the surface of the supernatant, as opposed to the lime tests, where only a sheen of oil was observed. This froth had to skimmed from the sample to observe the interface height.

The moisture content profile in Figure 4.34 and the fines content profile in Figure 4.35 show that the 7.5 and 10 ml/l tests resulted in very similar material, with no significant segregation observed. It is interesting to note that the 12.5 ml/l test showed a significant amount of segregation, which would explain why it did not settle to as low a void ratio as the other tests. It is not certain why this occurred, since only one test was performed at this concentration.

The addition of the acid results in an immediate reduction in the pH of the tailings, followed by a gradual recovery in pH as the tailings were mixed and then allowed to settle. 7.5 ml/l of acid drops the pH to about 5.5 and then it recovers to approximately 7.7 with time. The corresponding numbers for 10 ml/l and 12.5 ml/l are 4.0 to 7.3 and 3.0 to 6.0, respectively. This results in tailings that have a lower pH than the original tailings, as opposed


Normalized Height in Standpipe (h/H)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300
400
500
600
Moisture Content (%)
▲ 7.5 ml/l
■ 10.0 ml/l
◆ 12.5 ml/l



1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Normalized Height in Standpipe (h/H)
0
20
40
60
80
100
% Fines
▲ 7.5 ml/l
■ 10 ml/l
◆ 12.5 ml/l

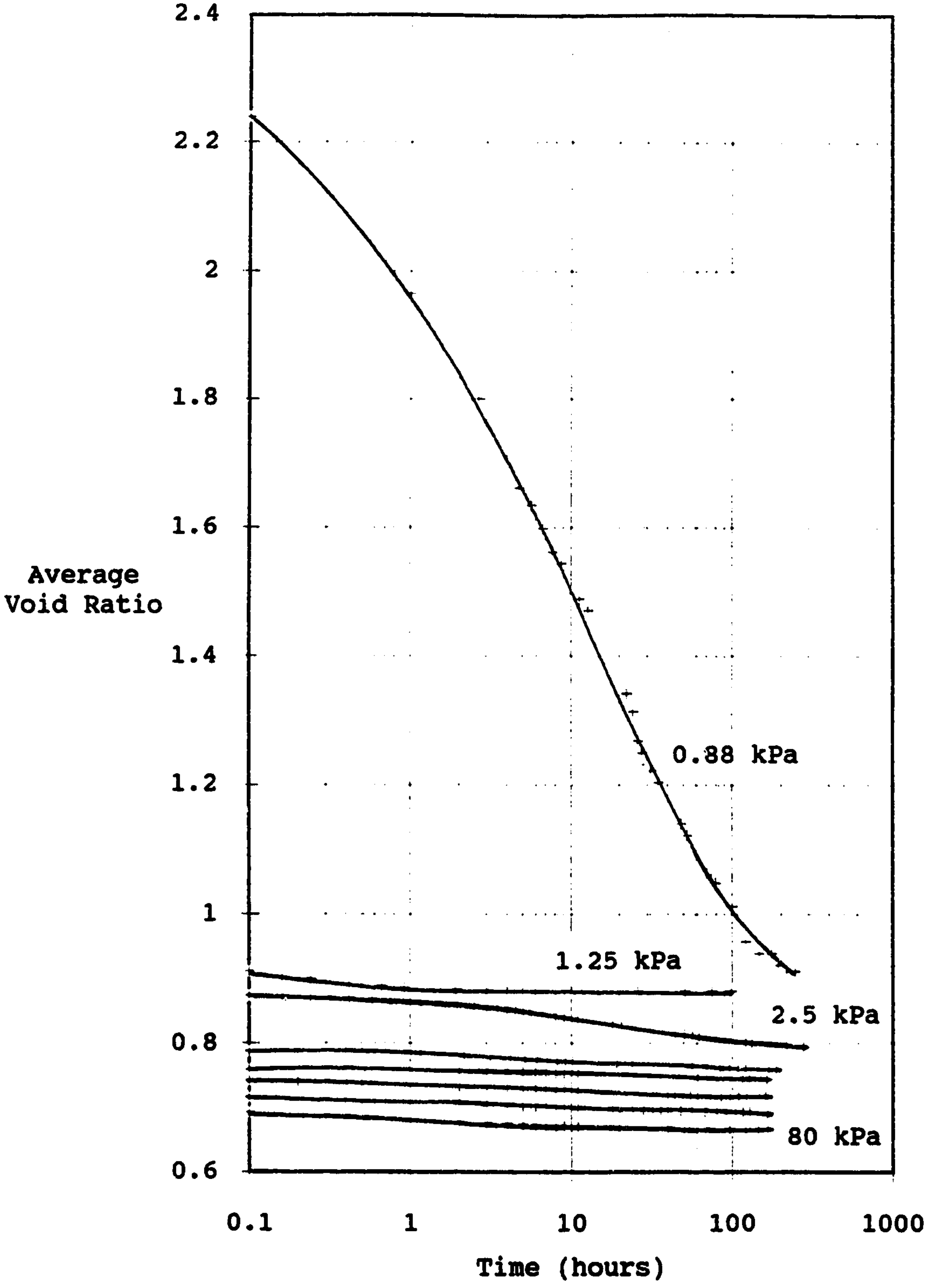
4.2.2 Consolidation Test Results

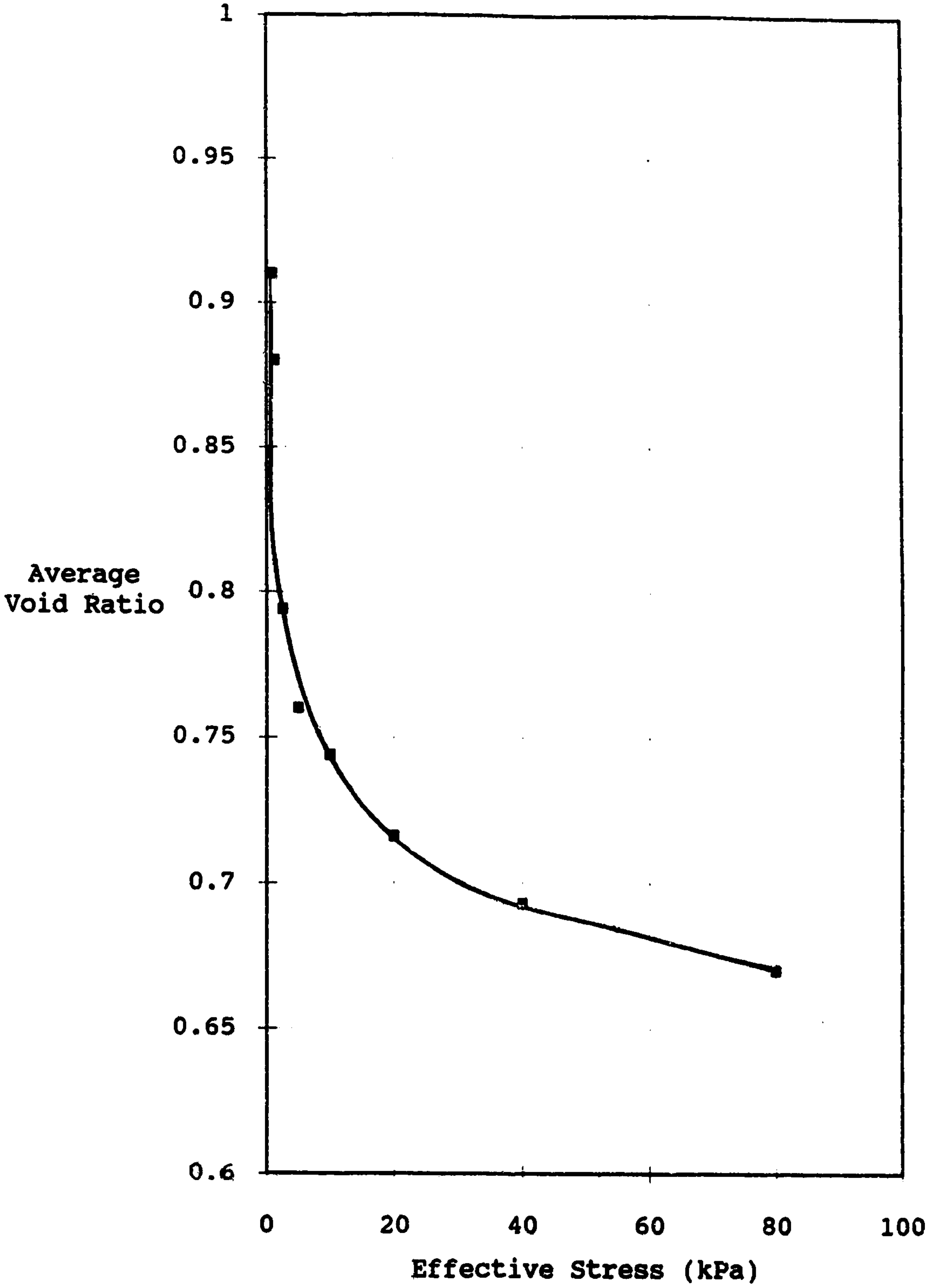
4.2.2.1 Step Loading Consolidation Tests

One step load slurry consolidation test was performed on the batch #2 tailings. It was performed on tailings with 800 ppm CaO added based on total weight. The average void ratio versus time plot for the self-weight consolidation and step loads is shown in Figure 4.36. The individual plots for each load are in Figures B.7 to B.14. The plot is quite similar to the same plot for the test on batch #1 tailings. The largest difference is the lower void ratio obtained after self-weight consolidation for the batch #2 tailings. The void ratio - effective stress plot in Figure 4.37 is almost identical to the plot for the batch #1 tailings.

The excess pore pressure plots for each load step are presented in Figures C.8 to C.14. The plots are similar to the plots for batch #1 tailings, showing a rapid decrease in pore pressure, likely indicating a significant amount of secondary compression. The plots for the 40 and 80 kPa loads, also show an excess pressure less than the increase in load, indicating that friction along the cylinder walls was beginning to build. The other load steps showed an initial excess pore pressure close to the increase in load.

The results from the permeability portion of the


2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
Average Void Ratio
0.88 kPa
1.25 kPa
2.5 kPa
80 kPa
0.1
1
10
100
1000
Time (hours)


1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
Average Void Ratio
0
20
40
60
80
100
Effective Stress (kPa)

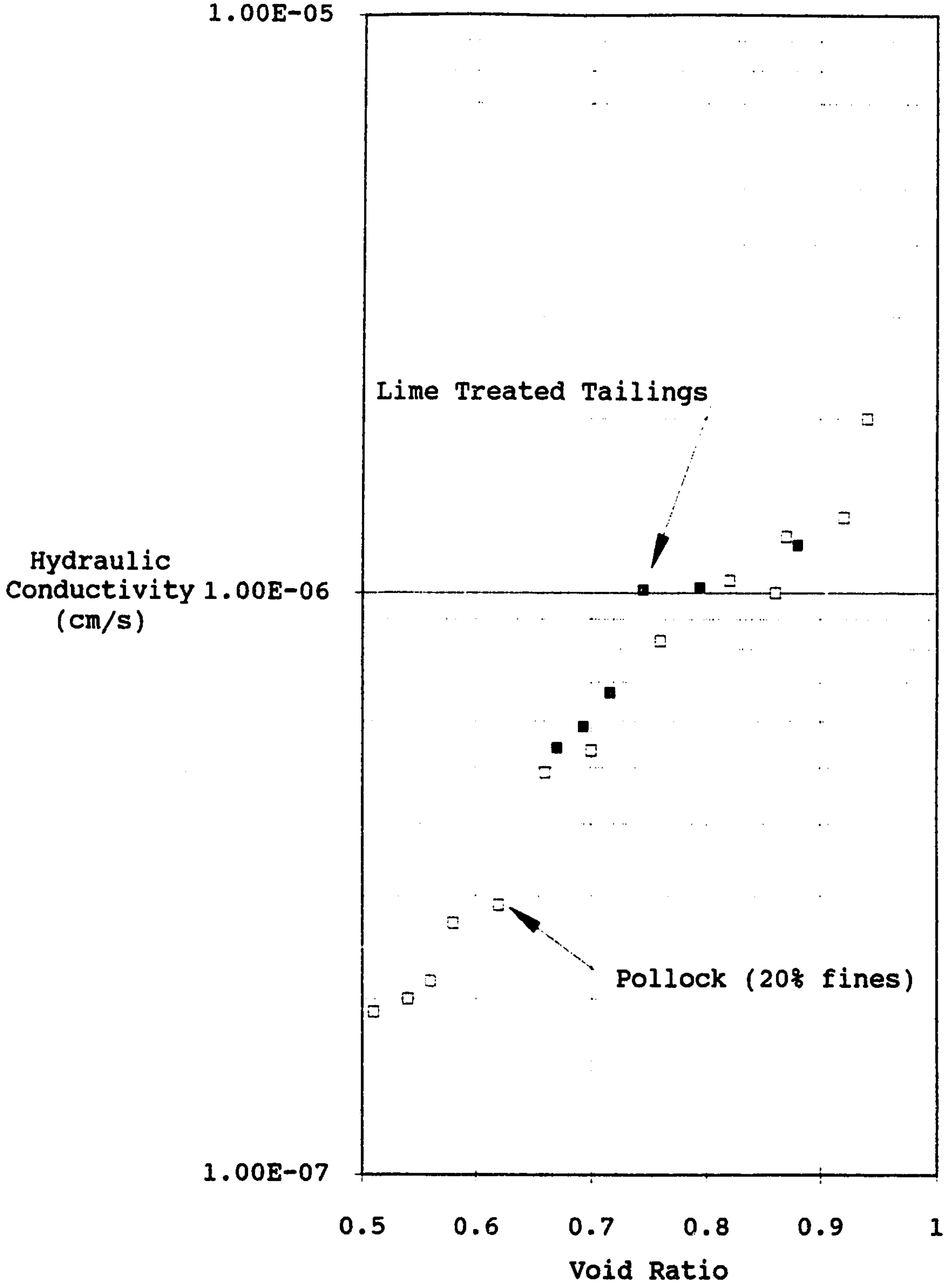


Figure 4.38 Tailings Batch #2 - Comparison of Permeability of Tailings

indicate that the permeability of the tailings is independent of the floc structure once a sand structure forms and is only dependent on the amount of fines and sand present. In other words, the same permeability relationship can be used for any tailings of a certain fines content, independent of the floc structure, once the material is below a void ratio of about 1.0. The permeability of the tailings will be discussed further in section 5.

4.2.2.2 Constant Rate of Deformation Consolidation Test Results

Three constant rate of deformation tests were performed on batch #2 tailings, two with 800 ppm CaO and one with 600 ppm CaO. The methods of Smith and Wahls (1969) and Wissa et al (1971) were again used. The void ratio - effective stress plots are shown in Figures 4.39, 4.40 and 4.41, respectively. The plots all show similar trends, although there is some range to the data. The three methods again result in curves that are very similar.

Figure 4.42 shows the results of all six consolidation tests performed here, along with the result from Pollock (1988) on an 80 % sand - sludge mixture. The constant rate of deformation curves are from the method Wissa et al (1971). The constant load tests plot in about the centre of the results, while the data from Pollock plot near the bottom of the range of tests.

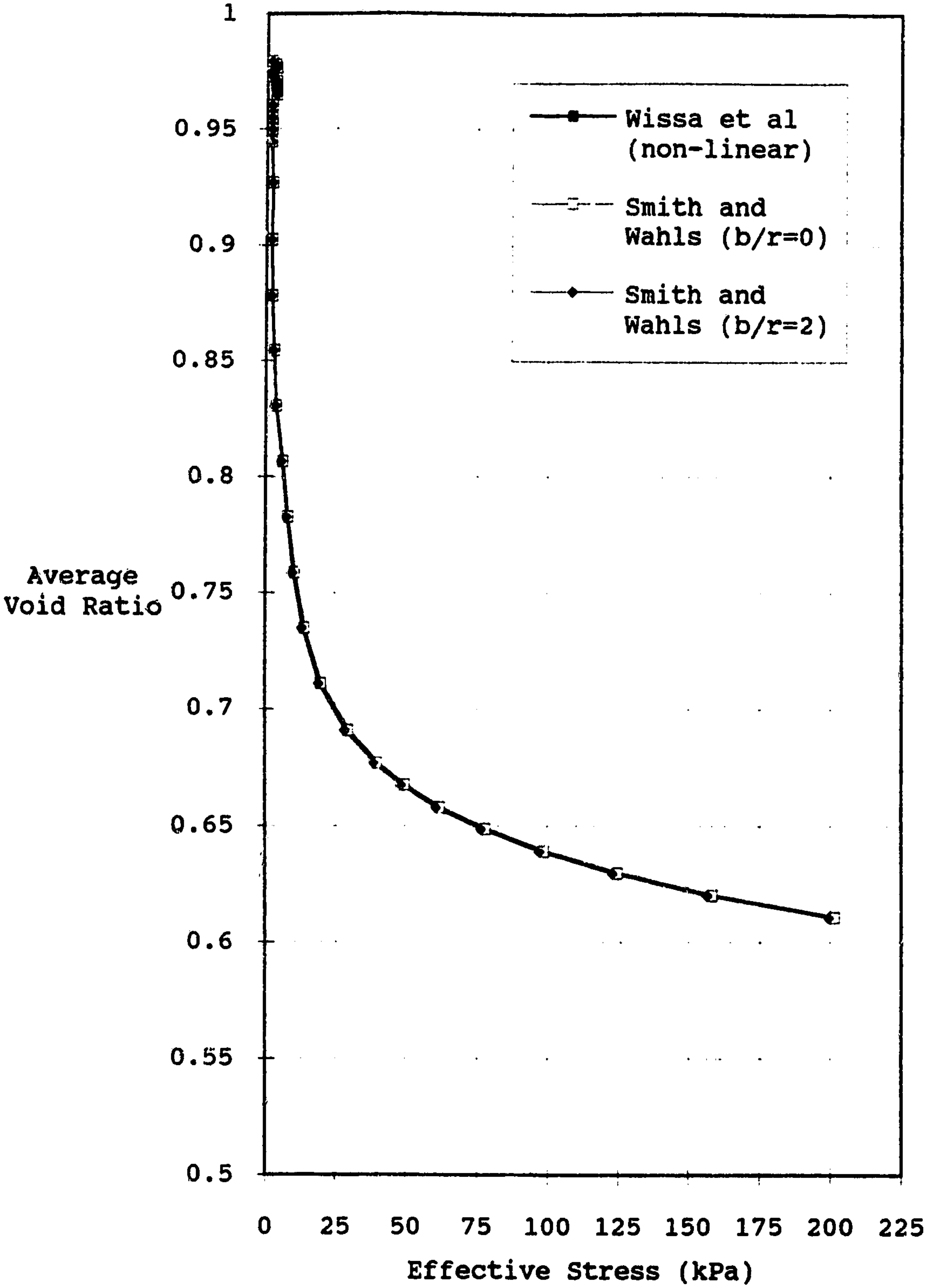


Figure 4.39 Tailings Batch #2 - Constant Rate of Deformation Consolidation Test - 800 ppm #1

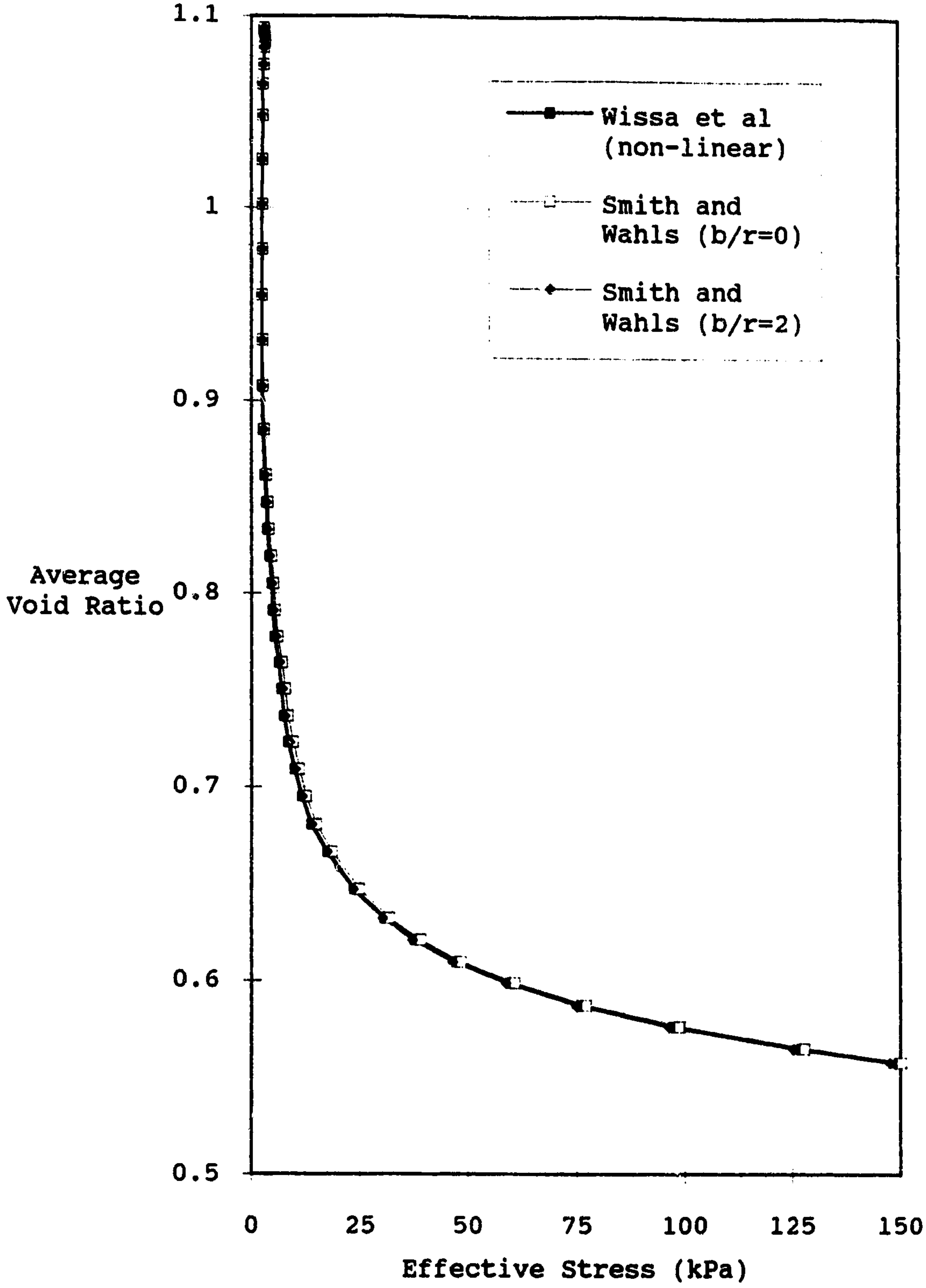


Figure 4.40 Tailings Batch #2 - Constant Rate of Deformation Consolidation Test - 800 ppm #2

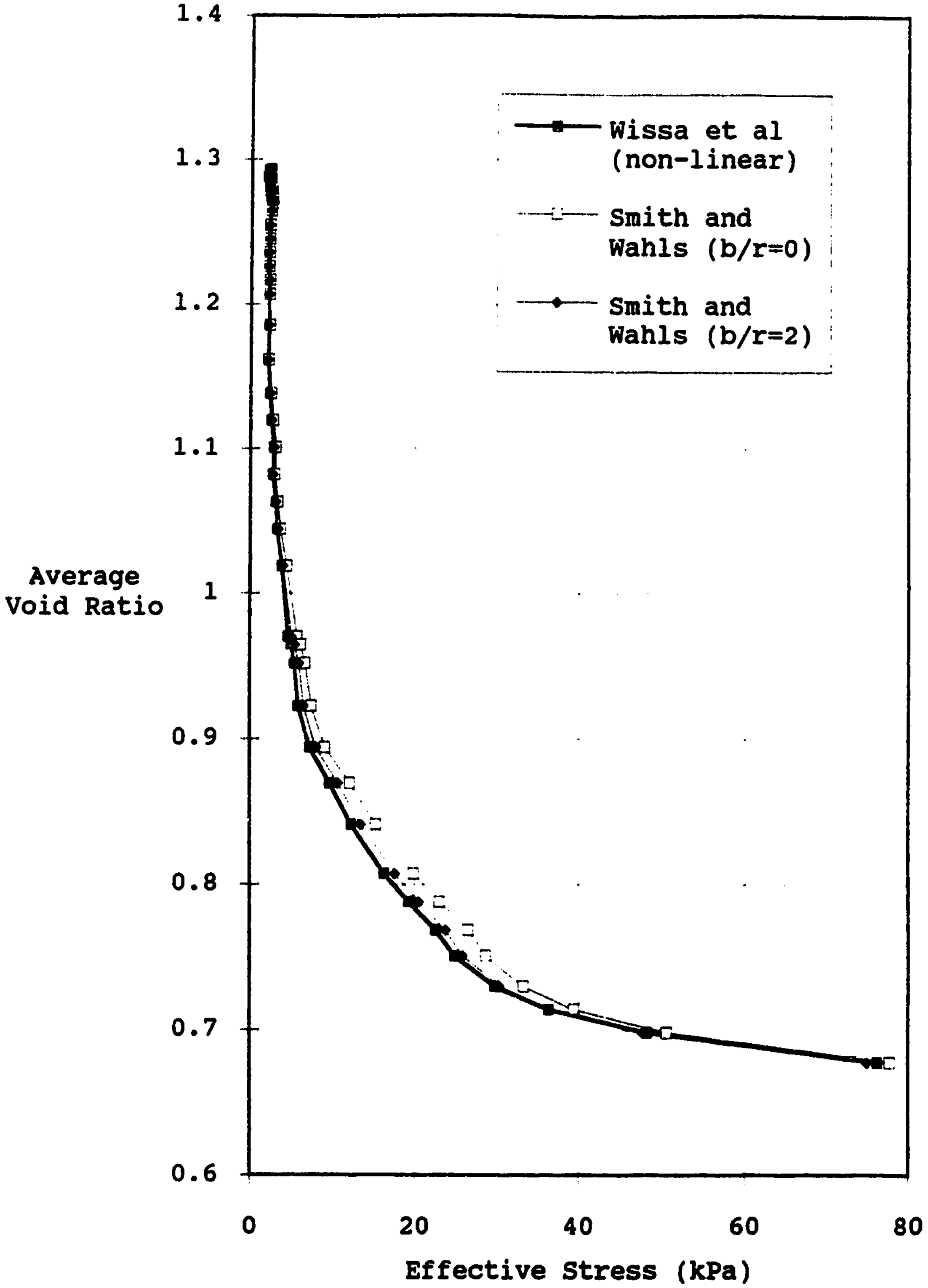


Figure 4.41 Tailings Batch #2 - Constant Rate of Deformation Consolidation Test - 600 ppm

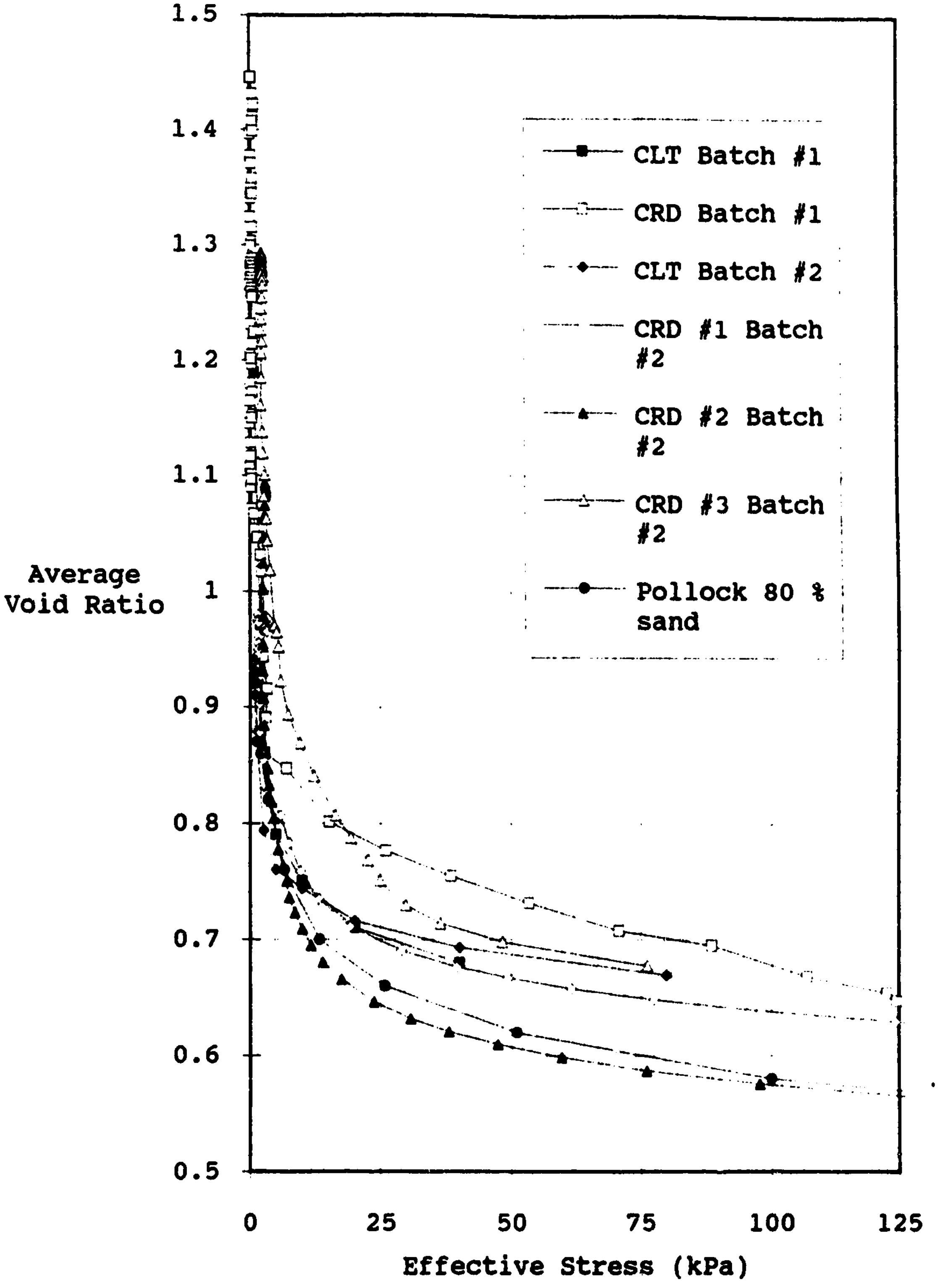


Figure 4.42 Comparison of Compressibility of Tailings

The excess pore pressure plots for the three tests are in Figures C.15 to C.17. They show a sharp increase in excess pressure at the start of the test, followed by a gradual decline at higher total stresses. The excess pore pressure as a fraction of the total stress is plotted versus void ratio for the three tests in Figures C.18 to C.20. They show that the excess pore pressures are much larger than recommended, even though much smaller strain rates than the test on batch #1 tailings were used (the tests lasted from 7 to 14 days). It appears that to maintain excess pressures in the required range of 3 to 20 percent, the test would have to be performed almost as slowly as a step load test.

4.2.3 Summary of Results

The results of the batch #2 tailings are much more consistent than for the first batch. An optimum lime content in terms of standpipe tests is in the range of 600 to 800 CaO by total weight. This results in a void ratio after self-weight consolidation of 0.9 to 1.0. The polymer A-110 was found to help mixes with lower concentrations of lime from segregating, but does not substantially help the self-weight consolidation of higher lime concentration mixes. The substantial added cost of the polymer would likely only be justified if it prevented segregation due to shearing during mixing or deposition, research not included in this study

4.3 Water Chemistry Results

The chemistry of the supernatant of selected tests was measured for selected properties by Norwest Labs, Edmonton. The results for Batch #1 are in Table 4.2 and for Batch #2 are Table 4.3. The results of similar tests from C-H Synfuels, 1984 are presented in Table 4.4. It is noted that the samples were taken at the end of the tests and the chemistry of the supernatant may have changed while it was sitting in the standpipe. The raw sample from batch #2 was from a barrel that had sat in the laboratory long enough for a clear water portion to form on top of the sample.

It is interesting to note that the pH of the tailings stream has increased due to build up of NaOH over time. The associated alkalinity has also increased substantially since the C-H Synfuels study. The high levels of bicarbonate in the present tailings stream explain the absence of any excess of Ca^{2+} until 3200 ppm CaO is added, as the bicarbonate reacts with the calcium ions, as noted earlier.

The water chemistry, for the parameters tested here, shows that lime addition would result in decant suitable for reclaim water, except for the high pH values. The pH increases rapidly with amounts of lime of 600 to 800 ppm to about 12.0 and then increases much more slowly with further addition of lime. The alkalinity of the water decreases with additions of lime to 600 - 800 CaO due to bicarbonate being consumed, then increases as hydroxide is released from

Table 4.2 Chemical Analysis of Tailings Batch #1 Decant

CaO Dosage (ppm)	As Rec.	600	600	600	600	400	800	1600	3200
A-110 Dosage ppm (polyelectrolyte)				6	6				
pH	10.1	9.3	12.3	9.3	12	10.2	10.4	12.6	13
Suspended Solids, mg/l	26	6	3	10	26				
Suspended Solids, % solids	0.0026	0.0006	0.0003	0.001	0.0026				
Turbidity, NTU	31.4	13.5	0.1	9.9	22.4	3.2	4	7.2	2.6
Total Hardness, mg/l CaCO3 (total Ca and Mg ions)	3.5	< 1.6	< 5.2	< 0.7	< 0.7				
Alkalinity, mg/l CaCO3	523	712	846	685	863	528	781	1292	
Bicarbonate, mg/l HCO3	213	593	< 1.0	651	< 1.0				
Hydroxide, mg/l OH-	-	-	211	-	139				
Total Organic Carbons, mg/l	4.2	4.7	2.9	4.2	3				
Si, mg/l	13	6.47	5.87	5.11	7.53	4.68	6.04	10	1.43
Ca ++, mg/l	0.7	0.5	1.9	< 0.1	< 0.1	1.8	1.8	0.8	212
Al +++, mg/l	5.05	2.89	1.51	1.98	2.49	0.41	1.18	0.86	0.38
Fe +++, mg/l	1.42	0.71	0.05	0.5	0.07	0.04	0.34	0.05	0.02

Table 4.3 Chemical Analysis of Tailings Batch #2 Decant

CaO Dosage (ppm)	Raw	400	600	600	800	800	1200	1600	800
A-110 Dosage ppm (polyelectrolyte)									6
pH	9.6	9.3	9.5	9.7	12.1	11.2	12	12.4	10.3
Suspended Solids, mg/l	116	14	27	6	505	7	6	6	9
Suspended Solids, % solids	0.012	0.0014	0.0027	0.0006	0.051	0.0007	0.0006	0.0006	0.0009
Turbidity, NTU	130	130	26	22.4	103	6.7	3.1	2.3	3.3
Total Hardness, mg/l CaCO3 (total Ca and Mg ions)	10.1	11.3	< 1.5	< 2.7	< 3.7	< 3.3	< 1.1	< 0.7	< 1.9
Alkalinity, mg/l CaCO3	1050	786	795	791	918	848	1140	1240	963
Bicarbonate, mg/l HCO3	819	696	600	204	< 1.0	< 1.0	< 1.0	< 1.0	287
Hydroxide, mg/l OH-	-	-	-	550	159	12.1	98.3	212	-
Total Organic Carbons, mg/l	3.7	4.1	4.6	4.5	3.4	3.3	3.5	3.5	3.6
Si, mg/l	7.49	18.3	4.91	4.32	7.49	6.1	6.79	6.5	4.39
Ca ++, mg/l	1.3	1	0.4	0.9	1.3	1.1	0.3	0.1	0.6
Al +++, mg/l	3.59	10.4	1.75	1.55	1.89	0.9	1.17	1.14	0.74
Fe +++, mg/l	0.91	1.98	0.39	0.34	0.11	0.03	0.1	0.16	0.04

Table 4.4 Chemical Analysis of Tailings Decant from C-H Synfuels (1984)

CaO Dosage	Raw Tailings	520 ppm	1300 ppm	1950 ppm	520 ppm
A-110 Dosage (polyelectrolyte)					4 ppm
pH	7.7	10.5	10.6	12	11.3
Suspended Solids, mg/l	33300	22.5	30	37	19.5
Suspended Solids, % solids	3.2	0.002	0.003	0.004	0.002
Turbidity, NTU	83	6.8	1.6	0.9	14
Total Hardness, mg/l CaCO3					
(total Ca and Mg ions)	32	<2	868	1300	20
Alkalinity, mg/l CaCO3	589	513	1824	2561	576
Total Organic Carbons, mg/l	174	58	34	31	37
SiO2, mg/l	22	104 ?	27	13	98 ?
Ca ++, mg/l	6	3	262	442	8
Al +++, mg/l	140	3.8	0.6	0.3	2.8
Fe +++, mg/l	12.1	0.2	0.1	0.1	0.2

relative measurement of the $CaCO_3$ required to adjust the pH a set amount). The suspended solids content and turbidity values are very low, reflecting how clear the water appears in the sample jar. The total organic carbon values are also very low. The levels of dissolved metals are also very low due to the high pH which tends to cause the metals to precipitate.

5. Field Predictions

The compressibility and hydraulic conductivity parameters determined from the testing program are used to predict tailings accumulation and consolidation in the field using two finite difference computer programs. The programs and methods of analysis are described in section 3.1. The laboratory parameters, in terms of power law functions, are determined in section 5.2 by comparing predicted settlement-consolidation curves to the laboratory data. Several cases from each batch of tailings are studied, covering the range of lime concentrations tested. The predicted curves from the acid tests would be similar to the lime predictions and are not included here. The predicted tailings accumulation and consolidation for each case is presented in section 5.3, for three rates of tailings accumulation.

5.1 Methods of Analysis

The finite difference consolidation method of Yong et al (1983) is combined with hindered settling theory in a finite difference program used to verify the laboratory data. The method has the advantage that it is easy to understand and program. The main limitation is that it uses a finite difference form of the traditional Terzaghi consolidation equation. The restrictions of small strains, constant material parameters and exclusion of self-weight of the traditional theory are eliminated by using a finite that is approximate (due to the restrictive assumptions in the governing equation) but is self-correcting if small enough time steps are used (due to the finite difference technique).

Hindered settling is modelled with the assumption that the tailings settle at the initial void ratio until an interface of a higher density material is reached. This is based on observations reported by Been and Sills (1981), Imai (1981) and Tan et al (1990a). For a standpipe test, the interface begins at the base of the cylinder and builds up with time. At the interface, the tailings collapse to a void ratio where effective stresses dominate the settling behaviour. This is called the beginning of consolidation void ratio. Consolidation occurs while hindered settling proceeds, until the consolidation-settling interface reaches the surface of the sediment. The solution may be inaccurate due to two reasons: 1) there is generally a transition zone between hindered settling and the onset of consolidation and 2) the void ratio during hindered settling may be higher than the initial void ratio due to water flowing upward from the consolidation zone.

Inputs to the program are the compressibility and hydraulic conductivity parameters (as power law functions), the initial sample height, the initial void ratio and the void ratio at the beginning of self-weight consolidation.

Due to time constraints, the ability to solve an upper program, so the program of Pollock (1988) was used to predict tailings accumulation with time. This follows the method of Somogyi (1980), using a fully implicit central finite difference analysis. Somogyi (1980) uses the theory of Gibson et al (1967), reformulated in terms of excess pore pressures. The theory is non-linear, includes self-weight of the soil and finite strains and places no restrictions on the initial void ratio condition.

The limitation of the theory is that is does not include hindered settling, so the average void ratio when hindered settling is complete, determined in the first program, is used as the initial void ratio. It would be more precise to use the void ratio at the beginning of consolidation, but since there is no laboratory data for compressibility until self-weight consolidation is complete, it would require considerable extrapolation of the data. It was found by trial and error that the initial void ratio, if above 1.0, had little effect on the moving boundary problem results, except for the highest rate of deposition, since hindered settling is so rapid.

A further refinement to the analysis would be to include hindered settling with the moving boundary problem, as outlined in Pane and Schiffman (1985) or Schiffman et al (1988). That theory combines hindered settling and finite strain theory into one equation, with a constant to control the rate of transition from hindered settling to the beginning of consolidation.

5.2 Verification of Material Parameters

Seven representative cases were chosen to study, three from the first batch of tailings and four from the second batch. The parameters are derived and then verified using the first computer program.

The compressibility and hydraulic conductivity relationships are determined as power law functions of the void ratio. The compressibility is assumed to be the same for all samples from each batch of tailings and is determined from the step load consolidation tests. The constant rate of deformation consolidation test results are not used due to problems with analysing the results as outlined in section 2.6.3.1.

Two void ratio - effective stress relationships were obtained from the step load test performed for each batch of tailings. Two power laws of the form $e = A\sigma'^{B}$ were found to fit the data best due to the sharp bend in the curve when the sand grains begin to come in contact. The power law parameters are listed in Table 5.1. The theoretical curves plotted with the laboratory data are shown in Appendix D, in Figures D.1 and D.2.

Void ratio - permeability relationships were determined by plotting the permeability from the hydraulic conductivity tests and the permeability calculated from the settlement curves and fitting power laws to each curve. The permeability is calculated from the settlement curves following the method of Tan et al (1990b). Separate

Table 5.1 Power Law Parameters

Case	Compressibility				Permeability	
	< 2.5 kPa		> 2.5 kPa			
	$e = A\sigma'^{B}$		$e = C\sigma'^{D}$		$e = Ek^{F}$	
	A	B	C	D	E	F
Batch #1						
400	1.104	-0.282	0.9177	-0.085	16.198	0.2176
600	1.104	-0.282	0.9177	-0.085	6.595	0.1534
3200	1.104	-0.282	0.9177	-0.085	11.711	0.1955
Batch #2						
600	0.8971	-0.134	0.8275	-0.048	17.535	0.221
800	0.8971	-0.134	0.8275	-0.048	6.7054	0.1557
1600	0.8971	-0.134	0.8275	-0.048	4.73	0.1306
800 (2 m)	0.8971	-0.134	0.8275	-0.048	2.729	0.0919

relationships are obtained for each of the seven cases. These are shown in Figures D.3 and D.4. For the shorter standpipe tests, power law relationships represent the data quite well, whereas the 2 metre standpipe has a zone where the permeability is constant at the beginning of the test, requiring two power law relationships to adequately represent the data.

The predicted versus actual settlement curves for five of the seven cases were quite good. The curves for the 800 ppm case for batch #2 are shown in Figure 5.1. The curves for the other four cases are presented in Figures D.5 to D.8. It was found by adjusting the beginning of consolidation void ratio, relatively good agreement between the actual and predicted curves could be obtained. This void ratio, along with the void ratio at the completion of hindered settling, is shown on the figures and is much higher for the tailings batch #1 tests. The higher void ratio at the beginning of consolidation is likely related to the lower self-weight of batch #1 tailings. The void ratio at the end of hindered settling is used as the initial void ratio for the field predictions.

The program does not handle the very slow hindered settling rate for the 600 ppm test from tailings batch #2 (Figure 5.2) very well. The steps in the predicted curve are due to the hindered settling-consolidation boundary stepping from one node to the next lower node in the finite

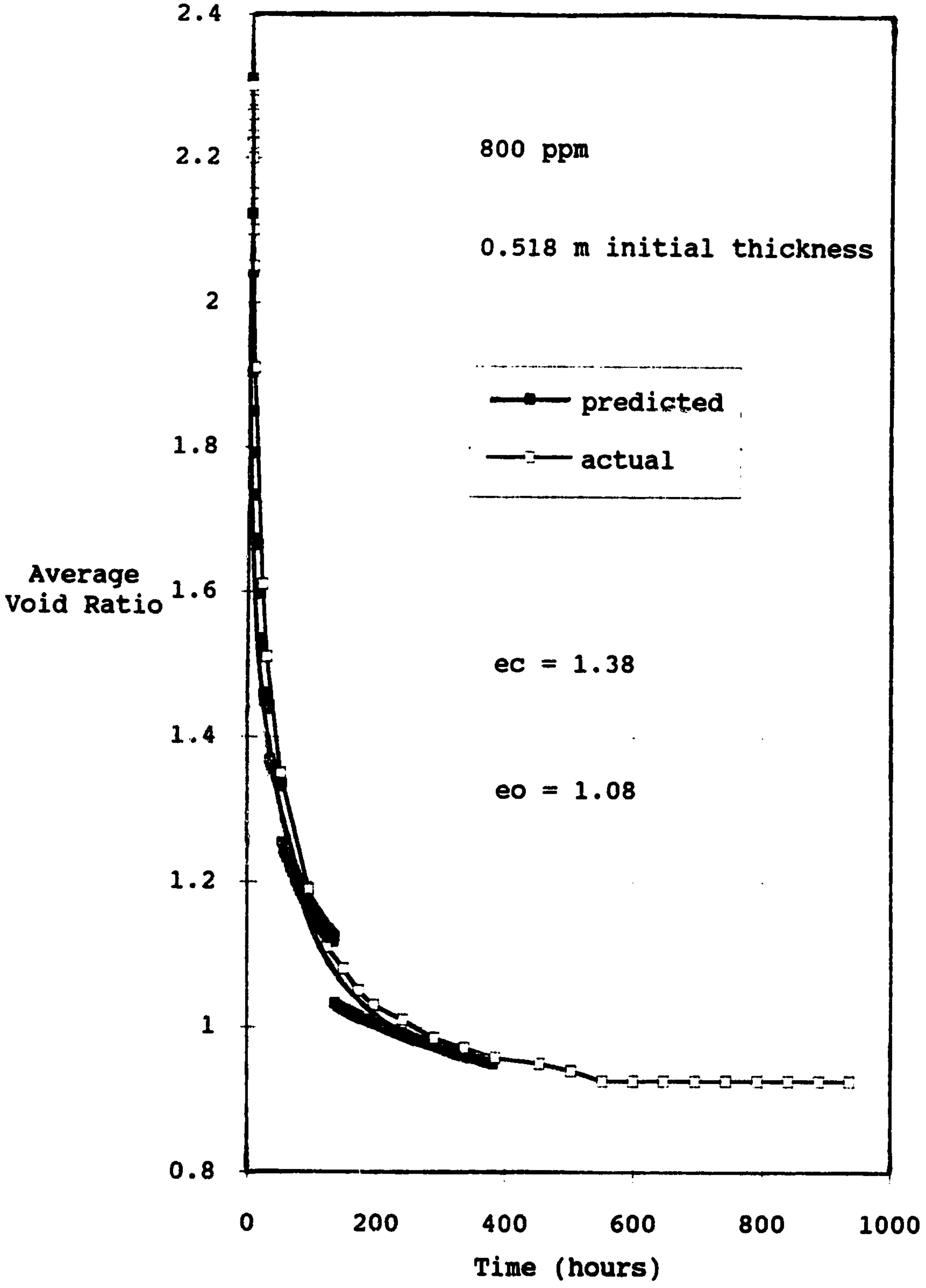


Figure 5.1 Predicted vs Actual Self-Weight Sedimentation and Consolidation - Tailings Batch #2

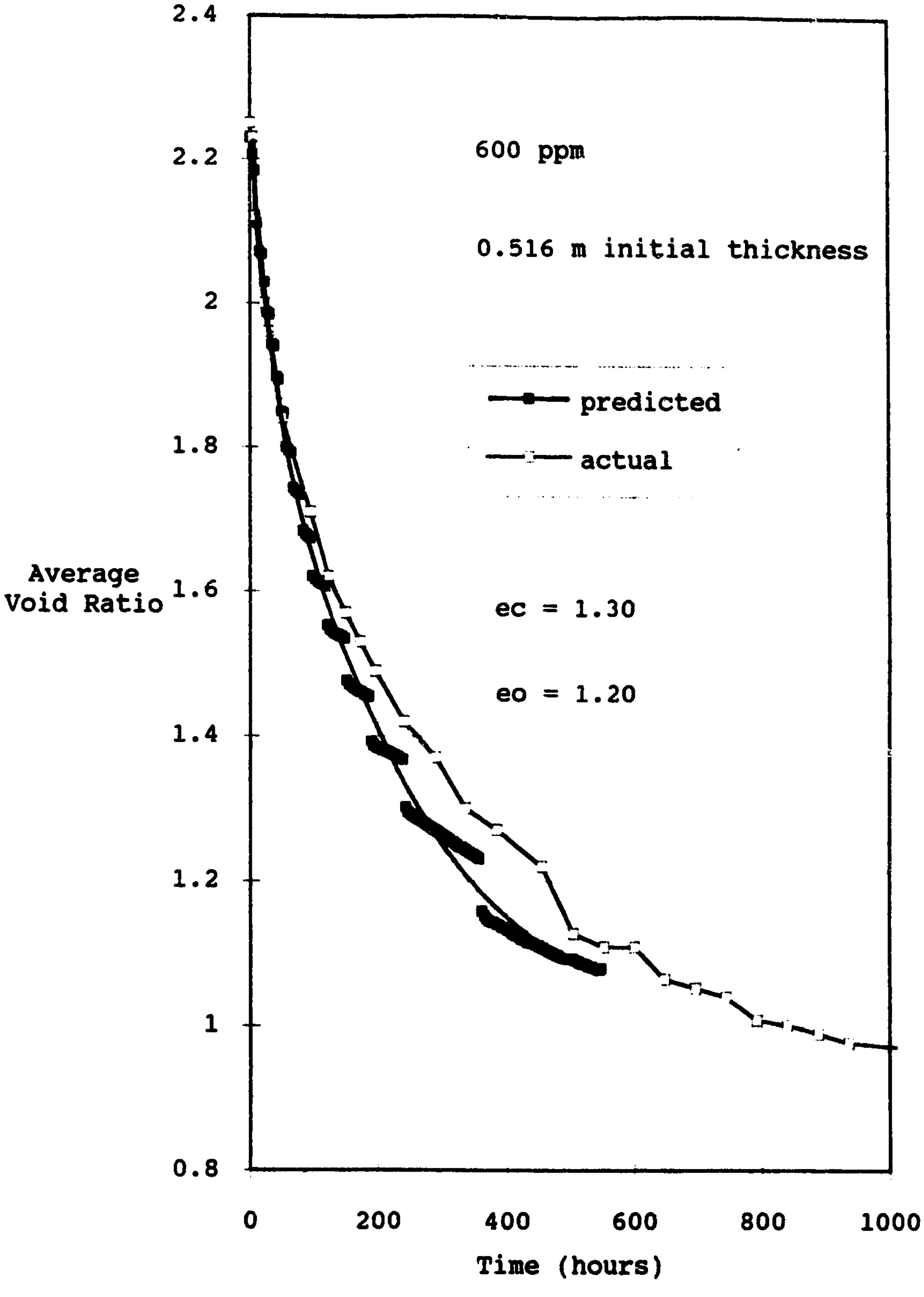


Figure 5.2 Predicted vs Actual Self-Weight Sedimentation and Consolidation - Tailings Batch #2

difference program. This is more exaggerated if the hindered settling rate is very slow.

The program does not predict the delayed consolidation that occurred for the 1600 ppm test from tailings batch #2 (Figure 5.3), although the end-of-consolidation void ratios agree quite well. This would be a concern in the field if the deposited layers are not thick enough to collapse the structure of the flocculated clays, when higher lime contents are used.

5.3 Prediction of Tailings Accumulation in the Field

Tailings accumulation is predicted using the average output of the Syncrude plant (270,000 tonnes of solids/day) and the estimated available pit area for disposal (13.2 km^2), for the seven cases mentioned earlier. This represents a rate of deposition of 9.16 m per year of total tailings, before settling and consolidation. Deposition rates of 18.31 m/yr and 36.62 m/yr (pit areas of 6.6 km^2 and 3.3 km^2) are also used for the 600 ppm, 800 ppm and 800 ppm (2 m) (batch #2) cases to determine the effect of increasing rates of deposition. The 800 ppm results are presented here, with the results of the other cases in Appendix D. The 600 ppm and 800 ppm (2 m) cases represent the range of possible results based on the available laboratory data.

The predictions are based on single drainage through the sample to the surface. This is reasonable since any bottom drainage, if the tailings are placed on sand, would

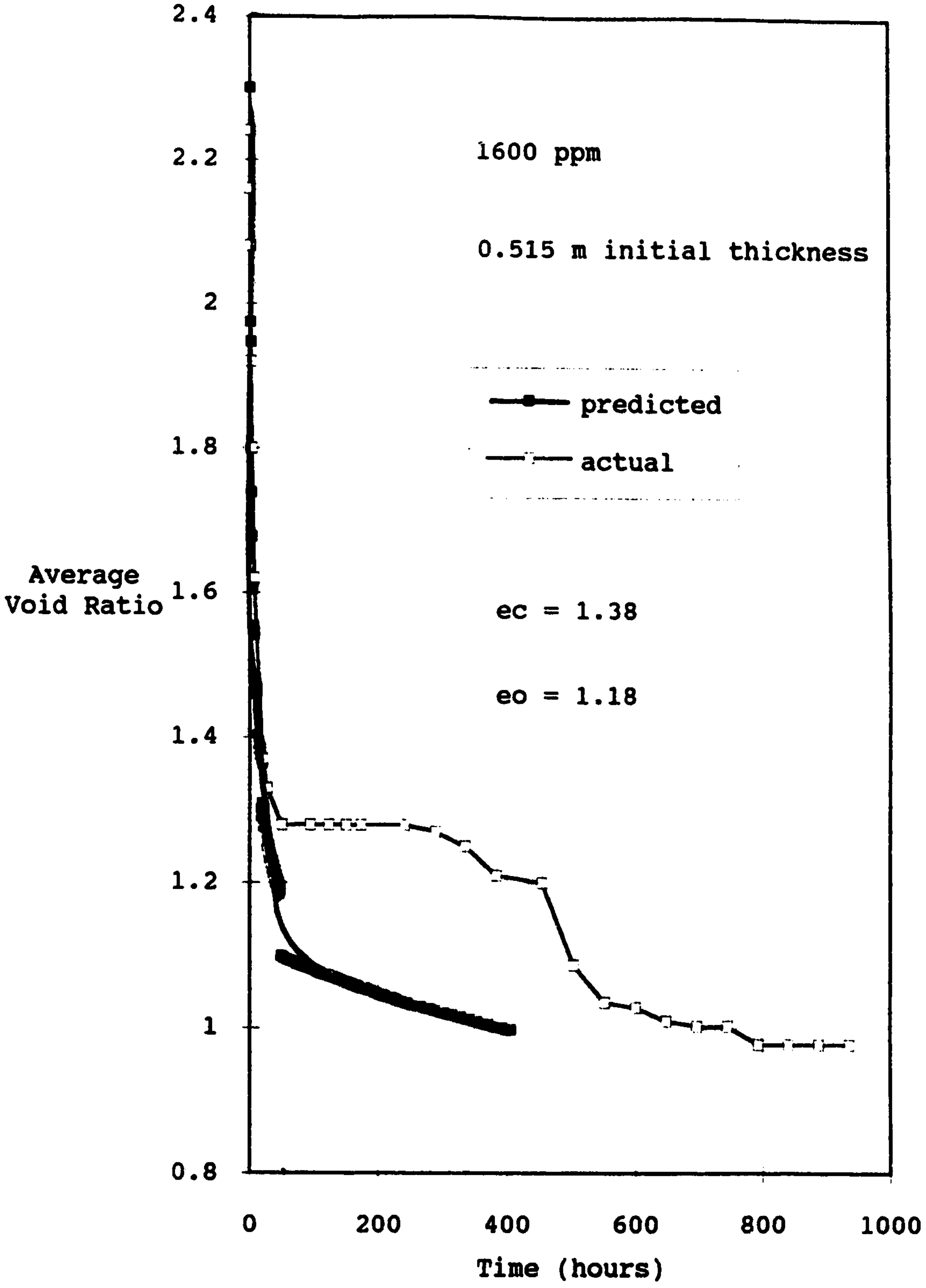


Figure 5.3 Predicted vs Actual Self-Weight Sedimentation and Consolidation - Tailings Batch #2

likely plug up with fines quite rapidly and have a small effect on the consolidation.

The output of the moving boundary program is: thickness of tailings with time, void ratio profile after one year, excess pore pressure after 120, 240 and 360 days.

The plot of tailings thickness with time for the three deposition rates for 800 ppm case is in Figure 5.4. This is the thickness of tailings below the end of hindered settling void ratio. It shows that the thickness of the highest rate is significantly more than twice that of the next lowest rate, indicating that it is much less consolidated. This can also be seen in the void ratio profiles in Figure 5.5, showing the highest rate to result in a highly underconsolidated state. The normalized excess pore pressure profiles in Figures 5.6 to 5.8 also show much larger excess pressures for the higher rates of deposition. The pore pressures are normalized by dividing by the instantaneous excess pore pressure, or in other words, the maximum effective stress that would develop, based on the weight of tailings above that point. The degree of consolidation after one year, based on the average amount of excess pore pressure dissipation, is 69 %, 47 % and 39 % for the 9.16, 18.31 and 36.62 m/yr rates of deposition, respectively. The initial excess pore pressure distribution is calculated from the buoyant unit weight of the tailings, if the entire amount of tailings were deposited instantaneously at the end of the year.

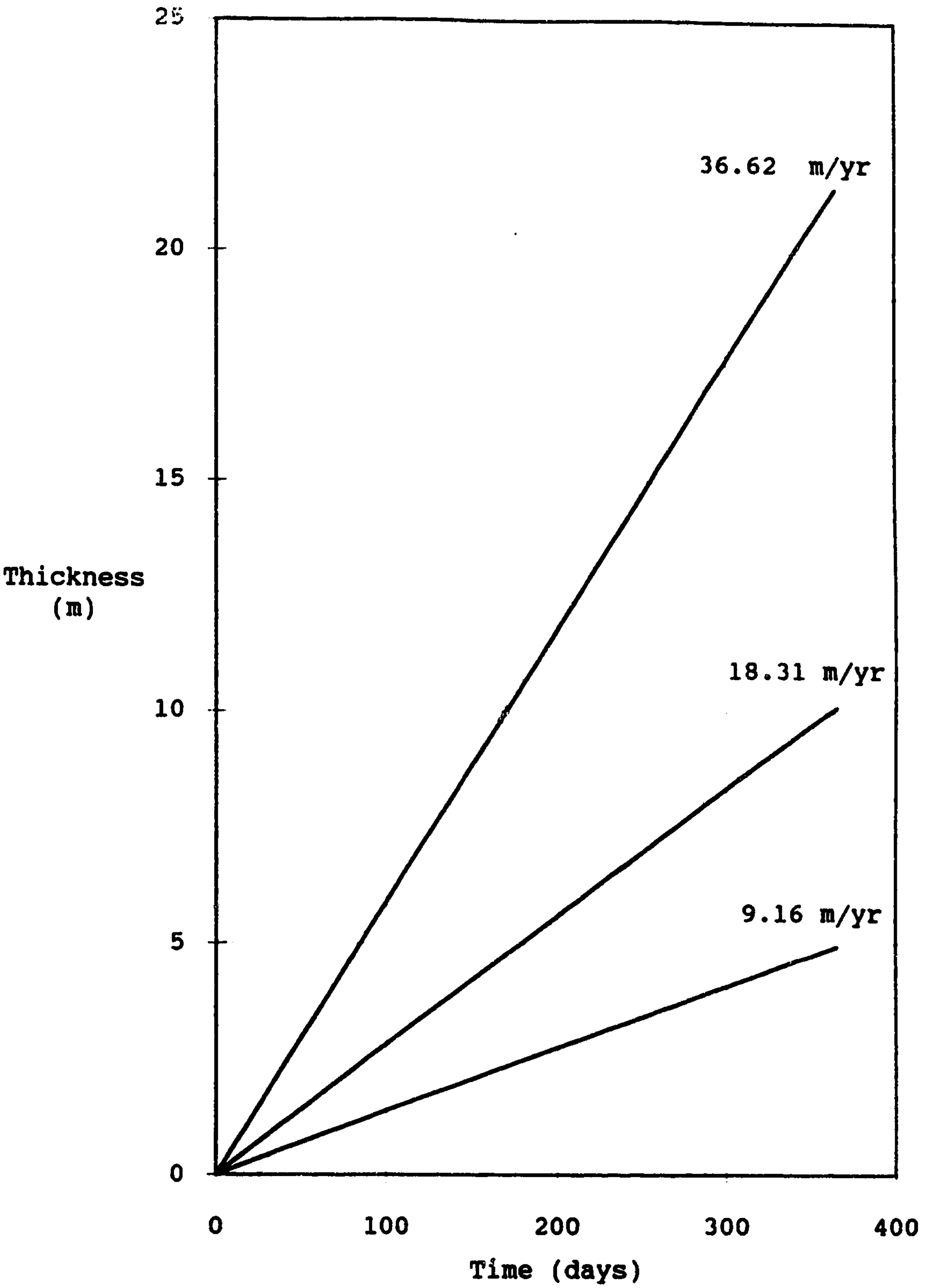


Figure 5.4 Tailings Accumulation In-Pit - Tailings Batch #2 - 800 ppm

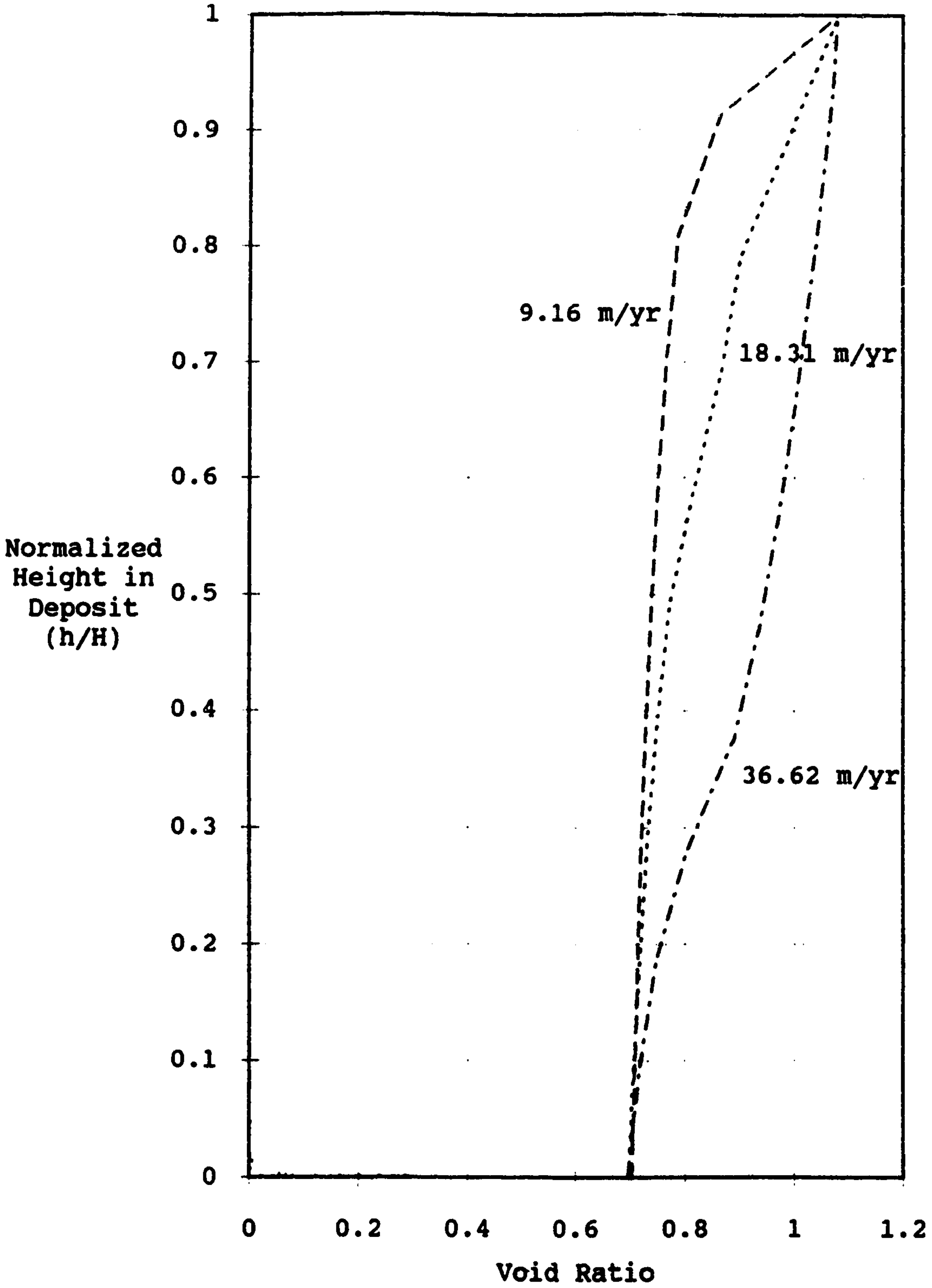


Figure 5.5 Void Ratio Profile after 1 Year - Tailings Batch #2 - 800 ppm

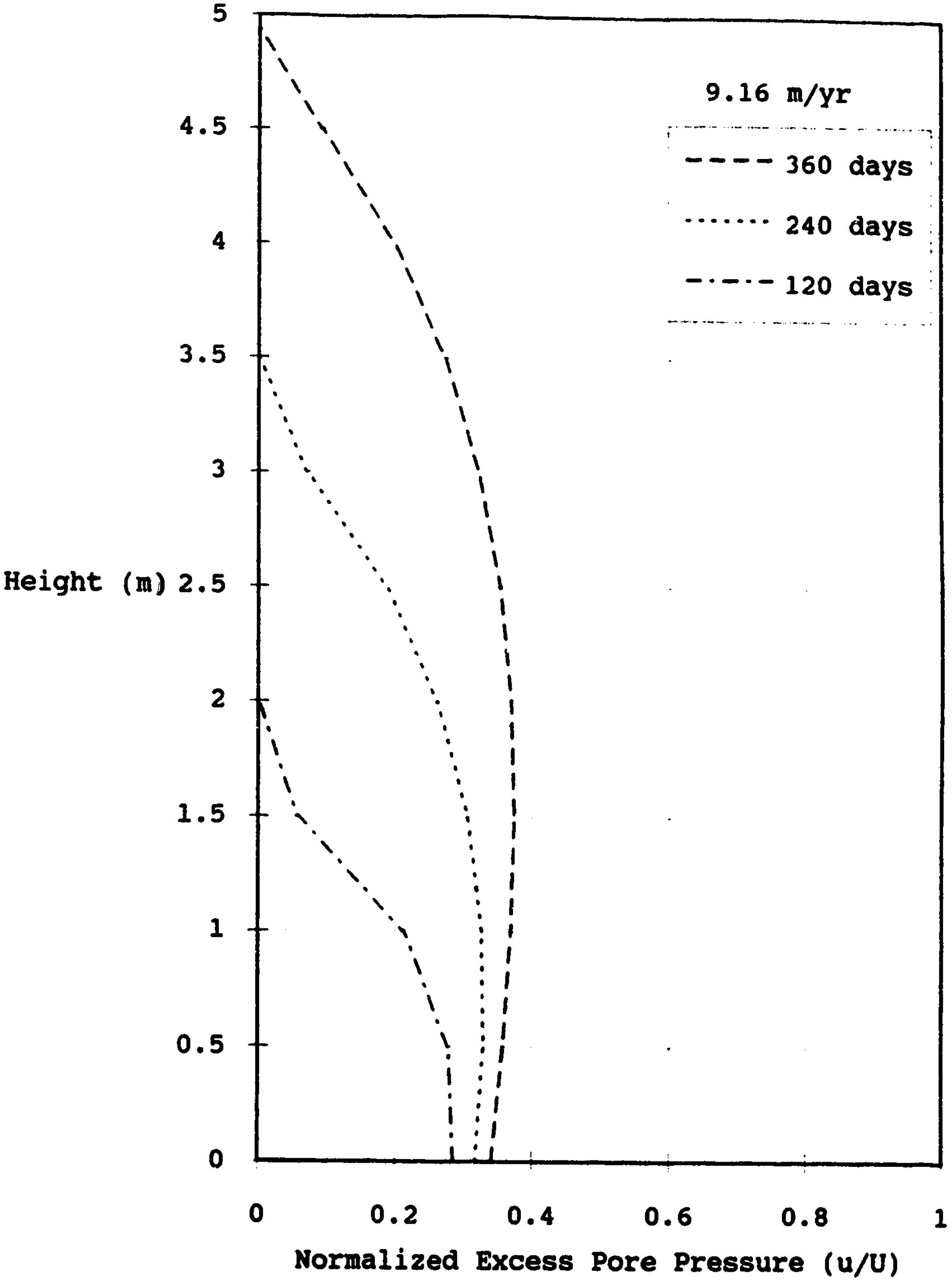


Figure 5.6 Normalized Excess Pore Pressures for In-Pit Disposal - Tailings Batch #2 - 800 ppm

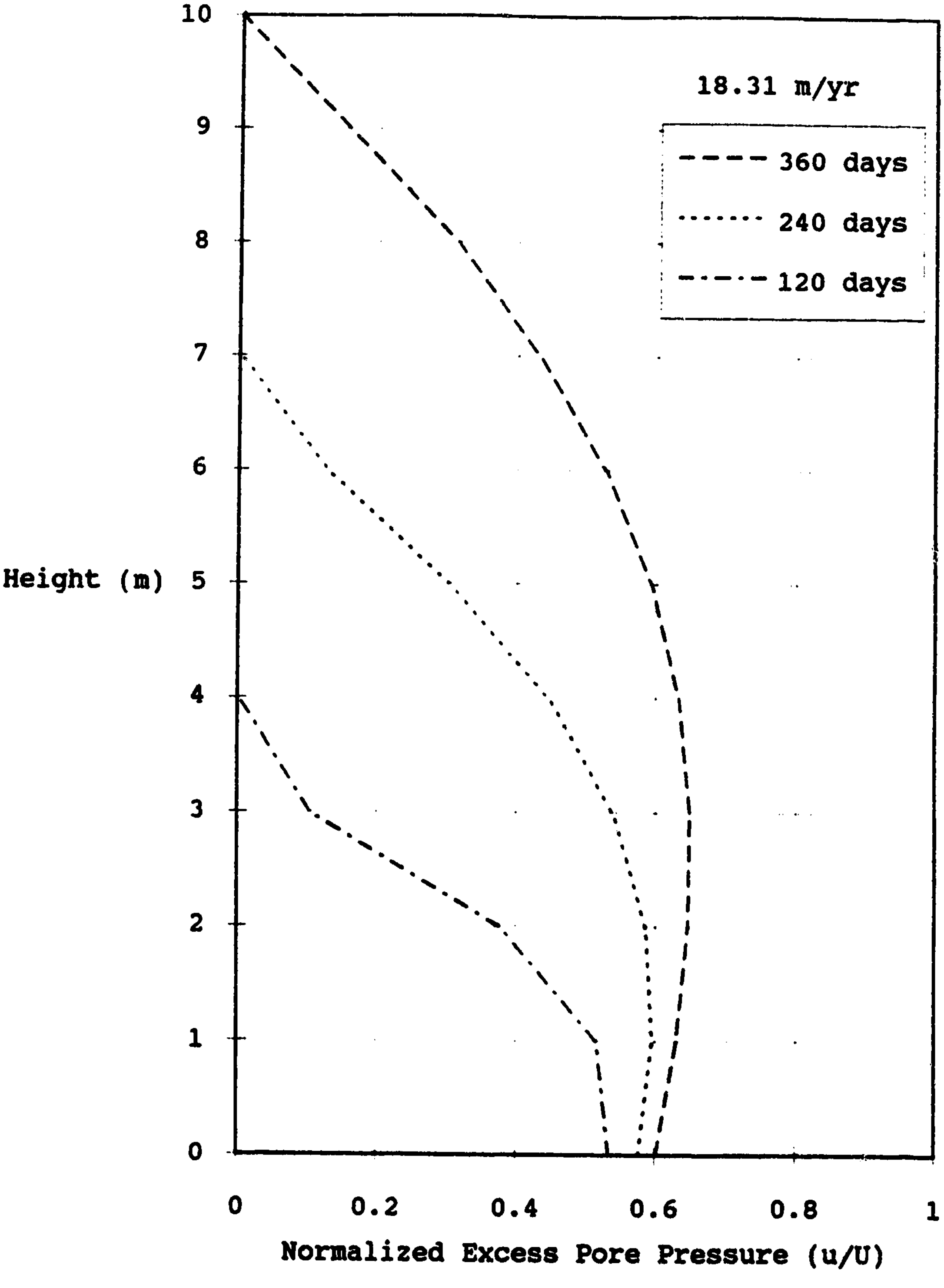


Figure 5.7 Normalized Excess Pore Pressures for In-Pit Disposal - Tailings Batch #2 - 800 ppm

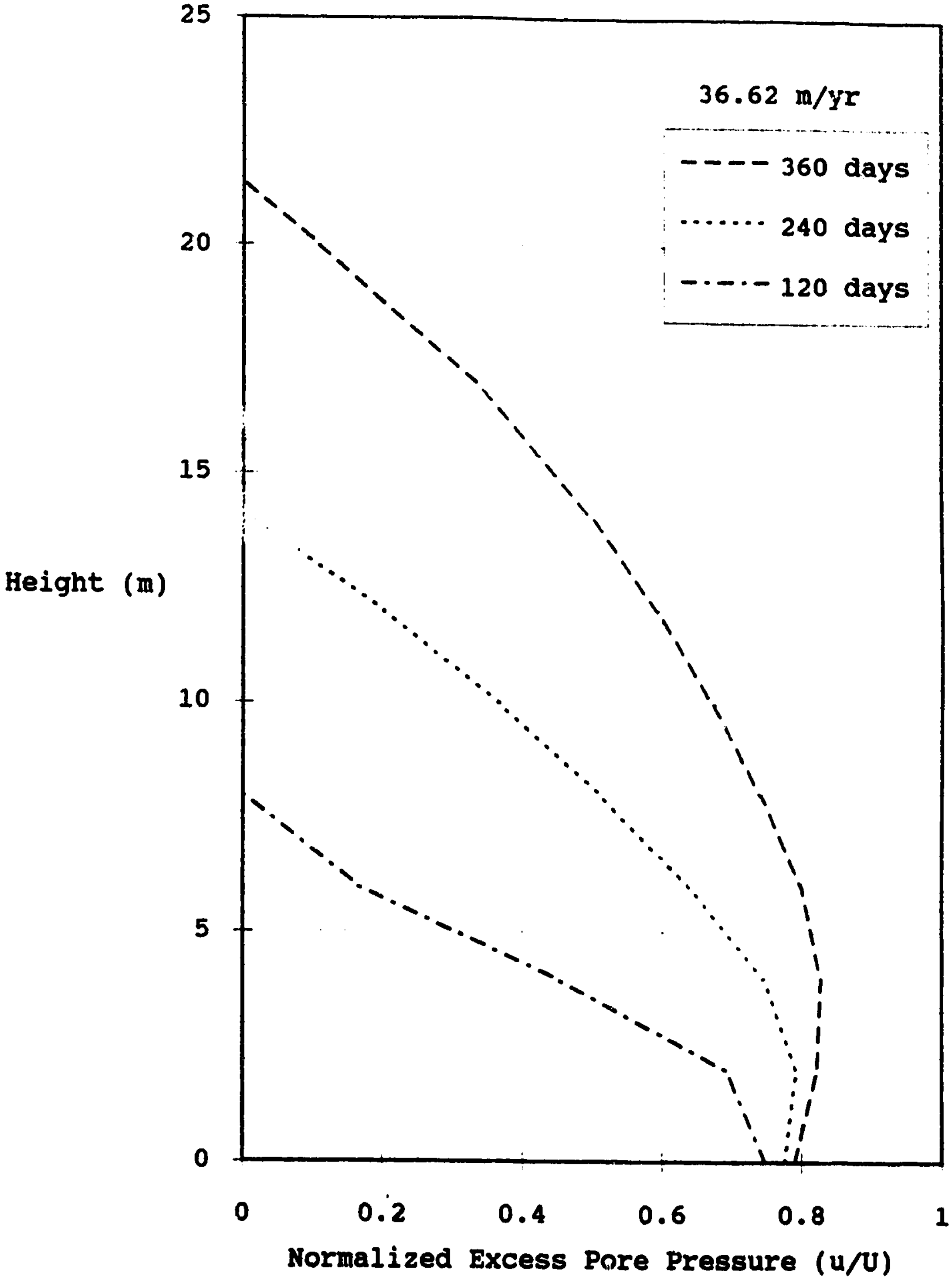


Figure 5.8 Normalized Excess Pore Pressures for In-Pit Disposal - Tailings Batch #2 - 800 ppm

The predictions for the other cases are in Appendix D. Comparison of the tailings thickness with time plots, in Figures D.9, D.17 and D.21, shows a much greater disparity between cases for the higher rates, up to a 4 metre difference for the highest rate. The void ratio profiles, in Figures D.10, D.18 and D.22, also show this, with the greater rates of deposition resulting in greater disparity between the results.

5.4 Summary

Power law functions of the laboratory data can be used to predict settlement-consolidation profiles accurately unless the self-weight consolidation is delayed, as in the higher lime content tests.

A moving boundary analysis of tailings deposition shows that at a rate of deposition of total tailings of 9 m/yr, all lime concentrations will result in 55 to 75 % consolidation, after depositing for one year.

For rates of deposition of 18 m/yr and 36 m/yr, the amount of consolidation decreases and the disparity between the amount of consolidation between cases increases. A rate of 18 m/yr is feasible if higher lime contents are used. Rates higher than 18 m/yr are also possible if channeling can be relied on to increase the permeability of the tailings at the beginning of consolidation.

6. Conclusions and Recommendations

6.1 Conclusions

1) Non-segregating mixes of total oil sand tailings can be achieved using either lime or sulphuric acid with deposition in a quiescent environment. From standpipe tests, the optimum lime content is in the range of 600 to 800 ppm CaO based on total weight and the optimum acid content is 7.5 to 10 ml/l using a 10 percent acid solution. These values are valid for a tailings stream of 45 to 55 % solids and 15 to 20 % fines (< 44 microns). The additives work by aggregating the clay particles in the tailings which prevents the sand grains from segregating.

2) A high molecular weight polymer does not substantially improve the settlement characteristics of a tailings mixture in quiescent conditions. It is possible that the polymer will help to prevent the tailings from segregating while being deposited in the field.

3) Settlement of the tailings mixes after flocculation occurs very quickly due to hindered settling. Self-weight consolidation continues after hindered settling at a much slower rate and for a longer time period. Channeling may occur with increasing thickness of rapidly placed layers, which increases the rate of hindered settling and possibly the early stages of self-weight consolidation.

4) The strain from hindered settling and self-weight consolidation can be considerable, even for deposits with an

initial thickness of 0.5 m or less (40 to 50 % depending on the initial void ratio).

5) Total tailings reach a sand matrix state at a void ratio of approximately 0.75, at effective stresses of approximately 5 to 10 kPa, for a fines content of about 17 % (< 44 microns). The effective stress for further consolidation increases dramatically after the sand grains come in contact.

6) The rate of hindered settling is dependent on the amount of additive used (or the degree of coagulation and flocculation) and if channeling occurs. An increased rate of settling generally occurs with increased amounts of additive, up to a limit of approximately 1200 ppm CaO or 12.5 ml/l 10 % H_2SO_4.

7) The interpretation of constant rate of deformation tests is complex and the effect of the magnitude of excess pore pressure on the test is still uncertain. Step loading tests result in more consistent compressibility relationships, although they require a longer testing period.

8) Adding lime to the tailings has no adverse effect on the tailings reclaim water except to increase the pH, based on the limited scope of the tests performed here.

9) A maximum rate of tailings deposition of 20 metres per year (initial thickness) appears possible if sufficient flocculation is achieved. This would result in 10 metres of semi-consolidated tailings (void ratio < 1). Higher rates

may be achieved if channeling could be relied on to increase the permeability of the tailings. If sufficient flocculation could not be achieved, then a deposition rate closer to 10 metres per year would be required.

6.2 Recommendations for Further Research

1) The effect of shearing on the segregation of flocculated mixtures of tailings needs to be investigated. This includes shearing while mixing the tailings and additives and shearing while depositing the tailings in the field.

2) The process needs to be tested on the complete range of solids and fines contents tailings to ensure that it works for the majority of cases.

3) A more complete analysis of the effect of various additives on supernatant water quality is required. This includes measuring more properties than was performed in this thesis and at various times after the supernatant is produced.

4) The potential of channeling with thicker initial thicknesses of tailings needs to be investigated. This would allow the tailings to be placed in smaller pits by increasing the rate of hindered settling and consolidation.

5) The effect of air entrainment on the segregation of tailings mixes, especially during deposition needs to be studied.

6) The average tailings stream is approximately 60° Celsius, while the tests were performed in this thesis at 20 to 25° Celsius. The effect of this temperature difference may be beneficial due to the decrease in the viscosity of water at higher temperatures and needs to be studied.

7) The field predictions should be performed with a program that includes simultaneous hindered settling and self-weight consolidation, with an upper moving boundary condition.

8) The effect of varying bitumen contents on the settlement, consolidation and water quality of the tailings mixes also needs to be studied.

References

Baillie, R.A. and Fear, V.D.J., 1975. "Method of Reducing Sludge Accumulation from Tar Sands Hot Water Process", Canada Patent 976,102 granted to Great Canadian Oil Sands, October 14, 1975, 13pp.

Bain, F. and Roberts, J.O.L., 1977. "Method of Sludge Disposal Related to the Hot Water Extraction of Tar Sands", U.S. Patent 4,008,146 granted to Great Canadian Oil Sands Ltd., February, 1977, 8pp.

Bates, R.L., Fondy, P.L. and Fenic, J.G., 1967. "Impeller Characteristics and Power", in Mixing - Theory and Practice Vol. I, Uhl, V.W. and Gray, J.B., eds, Academic Press, New York, pp. 111-178.

Been, K., 1980. "Stress-Strain Behaviour of a Cohesive Soil Deposited Under Water", Ph.D. thesis, University of Oxford, Oxford, England.

Been, K. and Sills, G.C., 1981. "Self-Weight Consolidation of Soft Soils: An Experimental and Theoretical Study", Geotechnique, Vol. 31, No. 4, pp. 519-535.

Behan, S.P. and Vendrinsky, D.A., 1976. "Method of Treating Effluents from Hot Water Extraction of Bitumen from Tar Sands", Canada Patent 1,000,632 granted to Great Canadian Oil Sands Ltd., November 30, 1976, 18pp.

Berkowitz, N. and Speight, J.G., 1975. "The Oil Sands of Alberta", Fuel, Vol. 54, pp. 138-149.

Boynton, R.S., 1980. "Chemistry and Technology of Lime and Limestone", John Wiley and Sons, Inc., 578 pp.

Bratby, J., 1980. "Coagulation and Flocculation", Uplands Press Limited, Croydon, England.

Bromwell, L.G. and Carrier, W.D., III, 1979. "Consolidation of Fine-Grained Mining Wastes", Proceedings of the Sixth Pan-American Conference on Soil Mechanics and Foundation Engineering, Lima, Peru, Vol. 1, pp. 293-304.

Bromwell, L.D. and Oxford, T.P., 1977. "Waste Clay Dewatering and Disposal", in Geotechnical Practice for Disposal of Solid Waste Materials, ASCE Specialty Conference, Ann Arbor, June 1977, pp. 541-558.

C-H Synfuels Limited, 1984. "Dry Tailings Disposal from Oil Sands Mining", unpublished report for Environment Canada, Vol. 1,2, App. A to D.

Camp, F.W., 1977. "Processing Athabasca Tar Sands - Tailings Disposal', The Canadian Journal of Chemical Engineering, Vol. 55, pp. 581-589.

Dusseault, M.B., 1977. "The Geotechnical Characteristics of Oil Sands", Ph.D. Thesis, University of Alberta, Edmonton, Canada.

Dusseault, M.B. and Scott, J.D., 1983. "Tailings Pond Behaviour and Characterization of Oil Sand Tailings Sludge', Particulate Science and Technology, Vol. 1, pp. 295-309.

Elliot, O.M., 1975. "Freeze-Thaw Separation of Solids from Tar Sands Extraction Effluents", Canada Patent 973,500 granted to Great Canadian Oil Sands Ltd., August 26, 1975, 22 pp.

ERCB, 1990. "Alberta's Reserves of Crude Oil, Oil Sands, Gas, Natural Gas Liquids and Sulphur, December, 1990", Reserves Report Series ST 91-18.

Erno, B.P. and Hepler, L.G., 1981. "Tailings Sludge Treatment", University of Lethbridge, AOSTRA, Agreement No. 140, Technical Report.

Fitch, B., 1979. "Sedimentation of Flocculent Suspensions: State of the Art", AIChE Journal, Vol. 25, No. 6, pp. 913-930.

Fuhr, B.J. and Liu, J.K., 1981. "Method for Controlling Flocculant Addition to Tar Sand Tailings", U.S. Patent 4,282,103 granted to Petro-Canada Exploration Inc., Alberta Government, Alberta Department of Energy and Natural Resources, Alberta Syncrude Equity, PanCanadian Petroleum Ltd., Esso Resources Canada Limited, Canada-Cities Service Ltd., Gulf Canada Resources Inc., August 4, 1981, 7pp.

Fuhr, B.J., Sanford, E.C. and Lemke, A.W., 1982. "Process for Separating Liquids and Solids from Whole Tailings from a Hot Water Extraction Process for Recovering Bitumen from Tar Sand", Canada Patent 1,131,574 granted to Petro-Canada Exploration Inc., Alberta Government, PanCanadian Petroleum Ltd., Esso Resources Canada Limited, Canada-Cities Service Ltd., Gulf Canada Ltd., Alberta Energy Co. Ltd., Hudsons Bay Oil and Gas Co. Ltd., Petrofina Canada Inc., September 14, 1982, 16pp.

Gibson, R.E., England, G.L. and Hussey, M.J.L., 1967. "The Theory of One-Dimensional Consolidation of Saturated Clays, I, Finite Non-Linear Consolidation of Thin Homogeneous Layers, Geotechnique, Vol. 17, pp. 261-273.

Hocking, M.B. and Lee, G.W., 1977. "Effect of Chemical Agents on Settling Rates of Sludges From Effluent of Hot-Water Extraction of Athabasca Oil Sands", Fuel, Vol. 56, pp. 325-333.

Hrudey, S.E. and Scott, J.D., 1981. "Water Reuse Needs of the Oil Sands Industry in Alberta", Water Reuse Symposium II, American Water Works Association Research Foundation, Washington, D.C., August 23-28, 1981, 13pp.

Hudson, H.E.,Jr., 1981. "Water Clarification Processes Practical Design and Evaluation", Van Nostrand Reinhold Company, New York, 353 p.

Imai, G., 1981. "Experimental Studies on Sedimentation Mechanism and Sediment Formation of Clay Materials", Soils and Foundations, Vol. 21, No. 1, pp. 7-20.

Jones, G.N., 1985. "Channel Formation in Sludge Thickening", in Fundamental Aspects of Sludge Characterization and Dewatering, Vesilind, P.A., ed., New England College, July 7-12, 1985, pp.219-239.

Kessick, M.A., 1982. "The Destabilization of Clay-Organic Dispersions by Polyacrylamide in the Presence of Calcium Ion", Alberta Research Council, 11 pp.

Kessick, M.A., 1982. "Treatment of Oil Sands Slimes and Modified Bitumen Recovery Process", Canada Patent 1,138,361 granted to Alberta Research Council, December 28, 1982, 23pp.

Kynch, G.J., 1952. "A Theory of Sedimentation", Trans. Faraday Soc., Vol. 48, pp. 166-176.

Lang, W.J. and Hentz, D.A., 1973. "Process for Flocculating Oil and Clay Containing Slimes", U.S. Patent 3,723,310 granted to International Minerals and Chemical Corp., March 27, 1973, 6 pp.

Lee, K., 1981. "Consolidation with Constant Rate of Deformation", Geotechnique, Vol. 31, June 1981, pp. 215-229.

Liu, J.K., Lane, S.J. and Cymbalisty, L.M.O., 1980. "Filtration of Hot Water Extraction Process Tailings", U.S. Patent 4,107,029 granted to Petro-Canada Exploration Inc. Alberta Government, Ontario Energy Corp., Imperial Oil Ltd., Canada-Cities Service Ltd., Gulf Oil Canada Ltd., September 30, 1980, 6pp.

Lyons, E.J., 1967. "Suspension of Solids", in Mixing - Theory and Practice Vol. II, Uhl, V.W. and Gray, J.B., eds, Academic Press, New York, pp. 225-260.

Marsh, C.R. and Shaw, W.H., 1984. "Tailings Management", Syncrude R and D Monthly Progress Report, 13(11), November, 1984.

McRoberts. E.C. and Nixon, J.F., 1976. "A Theory of Soil Sedimentation", Canadian Geotechnical Journal, Vol. 13, pp. 294-310.

Mikasa, M., 1965. "The consolidation of Soft Clay - A New Consolidation Theory and Its Application". Japan Society of Civil Engineers, Synopsis of J.S.C.E. Prize Papers for 1964 in Civil Engineering in Japan, pp. 21-26.

Mitchell, J.K., 1976. "Fundamentals of Soil Behaviour", John Wiley and Sons, Inc., 422 pp.

Olsen, H.W., Nichols, R.W. and Rice, T.L., 1985. "Low Gradient Permeability Measurements in a Triaxial System", Geotechnique, Vol. 35, No. 2, pp. 145-157.

Olson, R.E. and Daniel, D.E., 1981. "Measurements of Hydraulic Conductivity of Fine-Grained Soils", Permeability and Ground Water Contaminant Transport, American Society for Testing and Materials, Philadelphia, STP 746, pp. 18-64.

Olson, R.E. and Ladd, C.C., 1979. "One-Dimensional Consolidation Problems", Journal of the Geotechnical Engineering Division, Proceedings of the American Society of Civil Engineers, Vol. 105, No. Gt1, June, 1979, pp. 11-31.

Pane, V., Croce, P., Znidarcic, D., Ko, H.-W., Olsen, H.W. and Schiffman, R.L., 1983. "Effects of Consolidation on Permeability Measurements for Soft Clay", Geotechnique, Vol. 33, No. 1, pp. 67-72.

Pane, V. and Schiffman, R.L., 1985. "A Note on Sedimentation and Consolidation", Geotechnique, Vol. 35, No.1, pp. 69-77.

Pearse, M.J., 1984. "Use of Flocculants and Surfactants for Solid-Liquid Separation ", in Mineral Processing and Extraction Metallurgy, Jones, M.J. and Gill, P., eds., Institution of Mining and Metallurgy, pp. 443-452.

Pollock, G.W., 1988. "Large Strain Consolidation of Oil Sand Tailings Sludge", M.Sc. Thesis, University of Alberta, Edmonton, Alberta.

Prasad, B.D. and Joshi, R.C., 1985. "Tailings Pond Bitumen Extraction and Sludge Solidification", 3rd Intl. Conf. on Heavy Crude and Tar Sands, Long Beach, California, July, 22-31, Preprint, Vol.2, 17pp.

Rao, S.R., 1980. "Flocculation and Dewatering of Alberta Oil Sands Tailings", International Journal of Mineral Processing, Vol. 7, pp. 245-253.

Roberts, J.O.L., 1982. "Method of Surcharging with Sand the Sludge Layer of a Tar Sands Tailings Pond", Canada Patent 1,134,310 granted to Suncor Inc., October 26, 1982, 40pp.

Robinsky, E.I., 1978. "Tailing Disposal by the Thickened Discharge Method for Improved Economy and Environmental Control", Tailing Disposal Today, Vol. 2, Argall, G.O., Jr., Ed., pp. 75-95.

Sato, T. and Ruch, R., 1980. "Stabilization of Colloidal Dispersions by Polymer Adsorption", Surfactant Science Series, Vol. 9, Marcel Dekker Inc., pp. 121-130.

Schiffman, R.L., Vick, S.G. and Gibson, R.E., 1988. "Behaviour and Properties of Hydraulic Fill Structures", Hydraulic Fill Structures, ASCE Geotechnical Special Publication no. 21, Van Zyl, D.J.A. and Vick, S.G., eds, pp. 166-202.

Schmidt, W.K., 1987. "Recovery of Bitumen and Separation of Solids from Middlings and Tailings Associated with Hot Water Process", Canada Patent 1,223,834, July 7, 1987, 13pp.

Schutte, R., 1977. "Clarification of Tar Sands Middlings Water", Canadian Patent 1,003,776, January 18, 1977, 15pp.

Scott, J.D. and Chichak, M.F., 1984. "Report on Segregation Testing on Sand-Sludge-Flocculating Agent Mixes - Overburden Sludge Testing", Report to Syncrude Canada Ltd., June, 1986.

Scott, J.D. and Cymerman, G.J., 1984. "Prediction of Viable Tailings Disposal Methods", ASCE Symp. Sedimentation/ Consolidation Models, San Francisco, pp. 522-544.

Scott, J.D. and Dusseault, M.B., 1980. "Behaviour of Oil Sands Tailings", 33rd Canadian Geotechnical Conference, Calgary, Alberta, September 24-26, 1980, 16 pp.

Scott, J.D., Dusseault, M.B. and Carrier, W.D., III, 1986. "Large Scale Self-Weight Consolidation Testing", ASTM Symposium on Consolidation Behaviour of Soils, Ft. Lauderdale, Florida, 14 pp.

Scott, J.D., Taylor, D.E. and Scott, A.M., 1979. "Transportation of Oil Sands Tailings Over Long Distances", Third International Symposium, Transport and Handling of Materials, Vancouver, British Columbia, Canada, October 21-24, 1979, 22pp.

Smith, R.E. and Wahls, H.E., 1969. "Consolidation Under Constant Rates of Strain", Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers, Vol. 95, No. SM2, March 1969, pp. 519-539.

Somogyi, F., 1980. "Large Strain Consolidation of Fine Grained Slurries", Presented at the Canadian Society for Civil Engineering, Winnipeg, Manitoba, May 29-30.

Specken, G.A., 1977. "Method for Treating Fluids Containing Toxic Compounds and Suspended Colloidal Clays", Canadian Patent 1,007,772 granted to Wilson Mud Service Ltd., March 29, 1977, 17 pp.

Specken, G.A., 1978. "Clarification of Clay Containing Water", Canada Patent 1,030,674, May 2, 1978, 26pp.

Syncrude, (1979). "Syncrude Analytical Methods for Oil Sand and Bitumen Processing", AOSTRA Publication.

Syncrude, (1991). personal communication to Dr. N. R. Morgenstern

Tan, S.A., Tan, T.S., Ting, L.C., Yong, K.Y., Karunaratne, G.P. and Lee, S.L., 1988. "Determination of Consolidation Properties for Very Soft Clay", Geotechnical Testing Journal, Vol. 11, No. 4, pp. 233-240.

Tan, T.S., Yong, K.Y., Leong, E.C. and Lee, S.L., 1990. "Behaviour of Clay Slurry", Soils and Foundations, Vol. 30 No. 4, pp. 105-118.

Tan, T.S., Yong, K.Y., Leong, E.C. and Lee, S.L., 1990. "Sedimentation of Clayey Slurry", Journal of Geotechnical Engineering, Vol. 116, No. 6, pp. 885-898.

Tavenas, F., Leblond, P., Jean, P. and Leroueil, S., 1983. "The Permeability of Natural Soft Clays. PartI: Methods of Laboratory Measurement", Canadian Geotechnical Journal, Vol. 20, pp. 629-644.

Terzaghi, K., 1924. "Die Theorie der Hydrodynamischen Spanungserscheinungen und ihr Erdbautechnisches Anwendungsgebeit", Proceedings of the First International Congress of Applied Mechanics, Delft, The Netherlands, Vol. 1, pp. 288-294.

Tibbitt, J.M., 1977. "Clarification of Waste Waters Containing Dispersice Clay", Canada Patent 1,0210885 granted to Great Canadian Oil Sands Ltd., November 29, 1977, 22pp.

Tiller, F.M., 1981. "Revision of Kynch Sedimentation Theory", AIChE Journal, Vol. 27, No. 5, pp. 823-829.

Umehara, Y. and Zen, K., 1980. "Constant Rate of Strain Consolidation for Very Soft Clayey Soils", Soils and Foundations, Vol. 20, No. 2, June 1980, pp. 79-95.

Wissa, A.E.Z., Christian, J.T., Davis, E.H. and Heiberg, S., 1971. "Analysis of Consolidation at Constant Strain Rate", Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers, Vol. 97, No. SM10, Oct. 1971, pp. 1393-1413.

Yong, R.N., 1983. "Method for Treating Oil Sands Extraction Plant Tailings", Canada Patent 1,154,702 granted to Suncor Inc., October 4, 1983. 45pp.

Yong, R.N., Siu, S.K. and Sheeran, D.E., 1983. "On the Stability and Settling of Solids in Settling Ponds. Part 1. Piece-Wise Linear Consolidation Analysis of Sediment Layer", Canadian Geotechnical Journal, Vol. 20, pp. 817-826.

Znidarcic, D., Croce, P., Pane, V., Ko, H.-W., Olsen, H.W. and Schiffman, R.L., 1984. "The Theory of One-Dimensional Consolidation of Saturated Clays:III. Existing Test Procedures and Analysis", Geotechnical Testing Journal, Vol. 7, No. 3, Sept., pp. 123-133.

Znidarcic, D., Schiffman, R.L., Pane, V., Croce, P., Ko, H.-Y. and Olsen, H.W., 1986. "The Theory of One-Dimensional Consolidation of Saturated Clays: part V, Constant Rate of Deformation Testing and Analysis", Geotechnique, Vol. 36, No., 227-237.

Appendix A - Apparatus Details and Calibrations

Equipment Details

Pressure Transducers

The pore pressure at the base of the constant rate of deformation and step load consolidation cells was measured using Validyne Engineering Corporation Model DP15TL Multiple Range Pressure Transducers (S/N 33494,33495). This model allows different ranges of pressure to be measured by changing the diaphragm in the transducer. A 35 kPa diaphragm was used here. The transducers were calibrated using a Deadweight Tester Pressure Balance from Pressurements Ltd. (U.K.). The calibration curves for the transducers used for the constant rate of deformation and step load tests are in Figures A.1 and A.2, respectively and show both transducers are very linear.

Displacement Equipment

The travel of the piston in the constant rate of deformation and step load consolidation tests was measured using Hewlett Packard Linear Variable Displacement Transducers (LVDT's). The model used for the constant rate of deformation test was a 7 DCDT - 3000 with a travel of 15 cm and the calibration is shown in Figure A.4. A 24 DCDT - 3000 (S/N 1185) with a travel of 15 cm was used for the step load test. It's calibration is shown in Figure A.3. The transducers were calibrated using a high precision micrometer. The calibration curves for both LVDT's have a correlation coefficient close to one, showing them to be very close to linear.

Load Cells

The load in the piston rod for the step load consolidation cell was measured using a load cell constructed at the University of Alberta by the head technician, Gerry Cyre. The load cell has a maximum range of 600 kg. The cell was calibrated using a deadweight tester. The calibration curve is shown in Figure A.5 and shows the output is linear except for the first 20 kg of load.

The load in the piston rod for the constant rate of deformation consolidation tests was measured using an Omega Engineering Inc. Model LCC Load Cell (S/N 398758). The capacity of the load cell is 900 kg. The calibration curve is shown in Figure A.6 and shows the cell to be highly linear.

Pressure System for Step Load Cell

For the loads above 5 kPa for the step load cell, a diaphragm air cylinder from Bellofram Products Company was used. This transfers air pressure to a load on the piston rod. The model used had the following specifications:

Type: D

Size: 36

Series: F

Rod: BP

Lot: 0012

Bore: 6.8 in.

Stroke: 5.4 in.

The air pressure applied to the air cylinder was regulated using a Moore Instruments Ltd. Nullmatic Pressure regulator, Model 40-200 (S/N 4588).

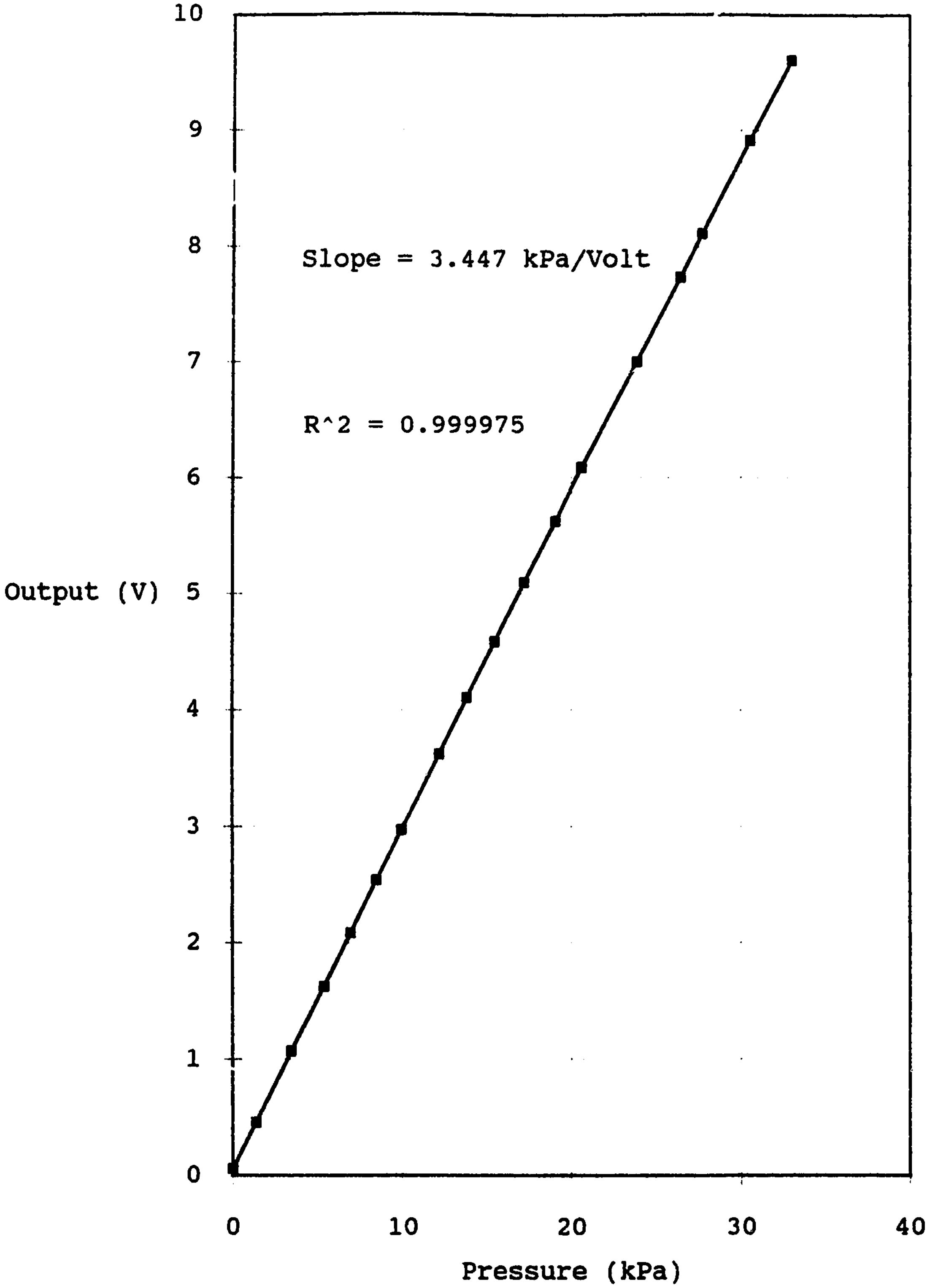


Figure A.1 Calibration of Pressure Transducer #1

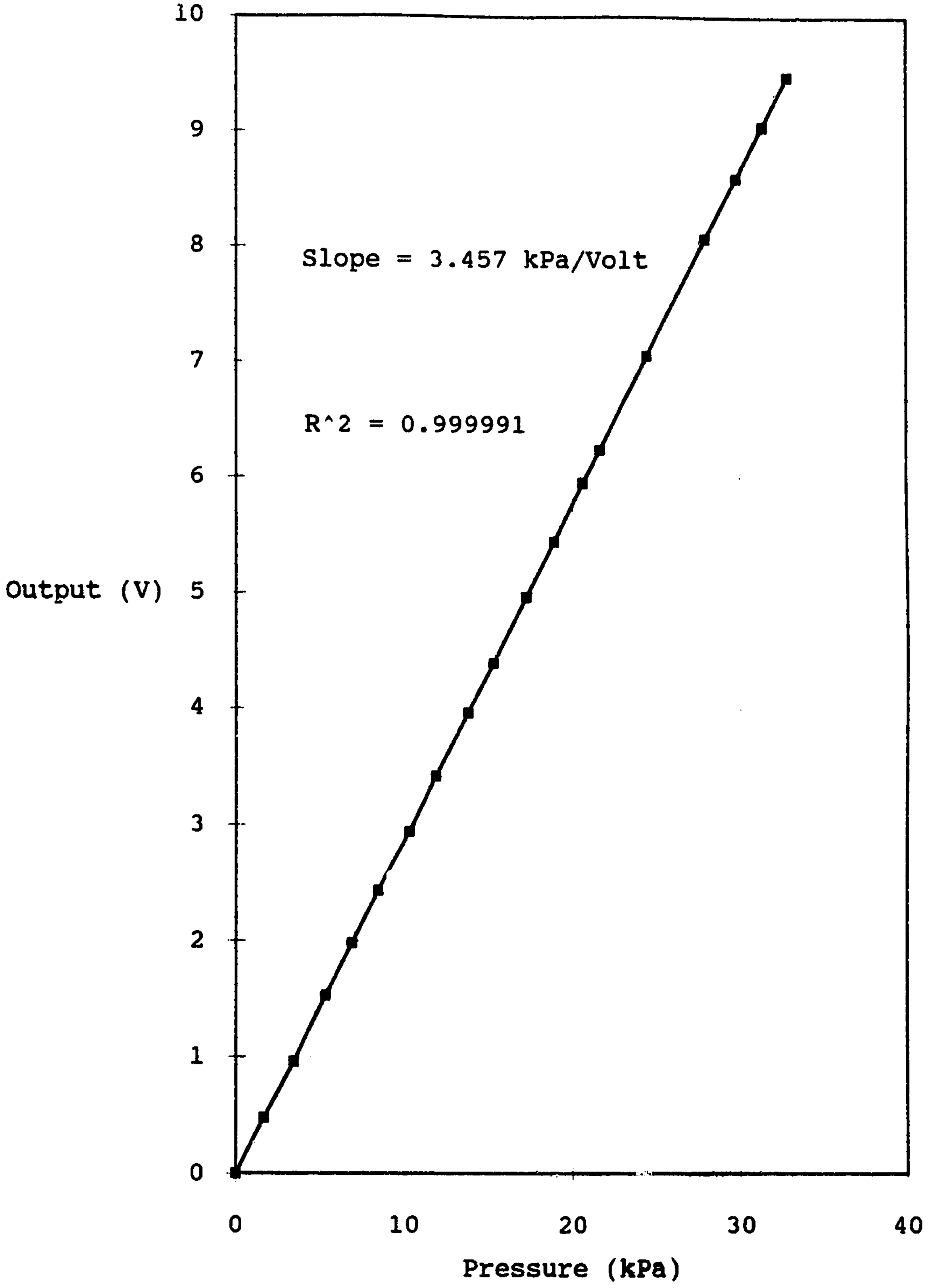


Figure A.2 Calibration of Pressure Transducer #2

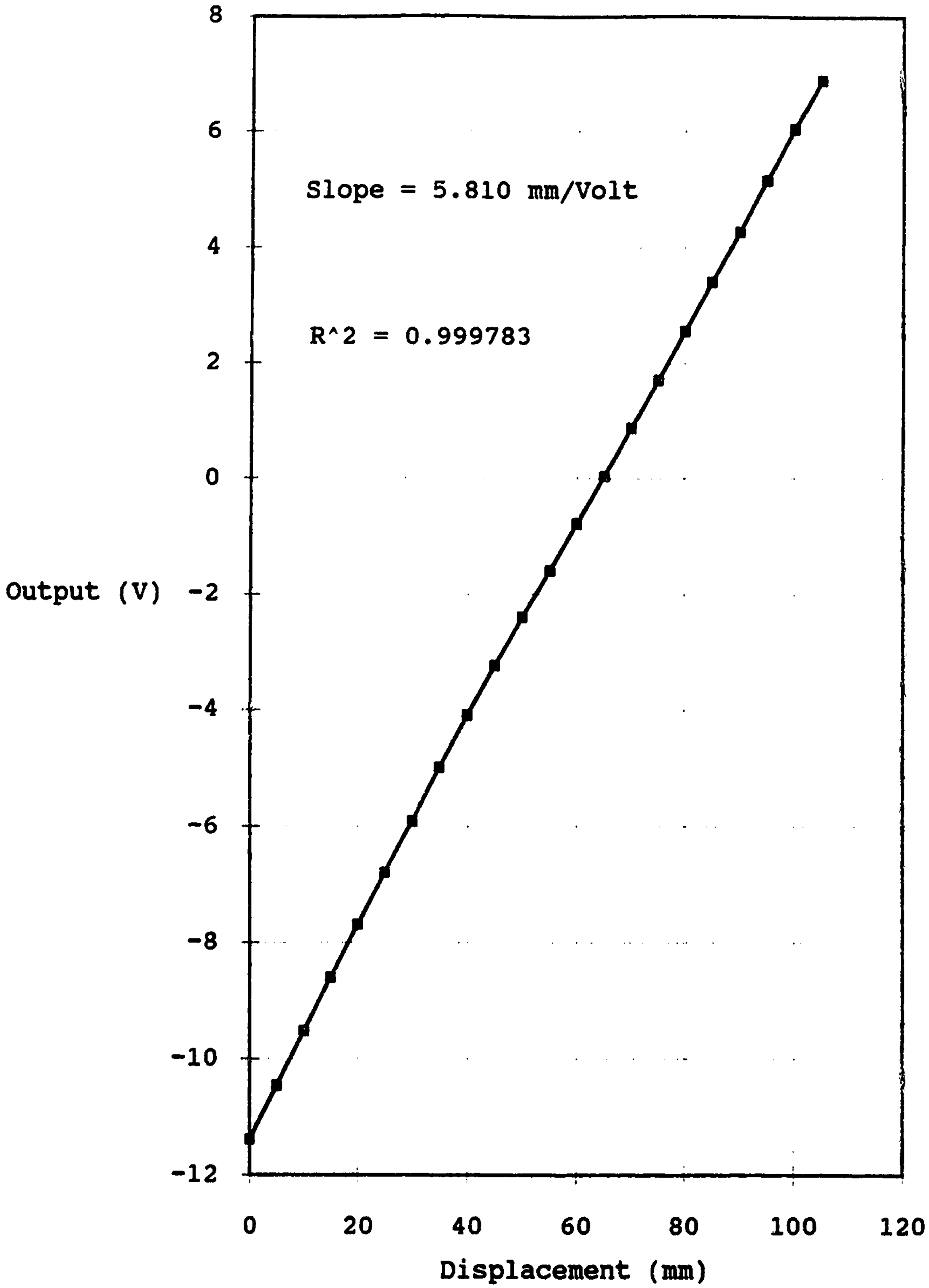


Figure A.3 Calibration of LVDT #1

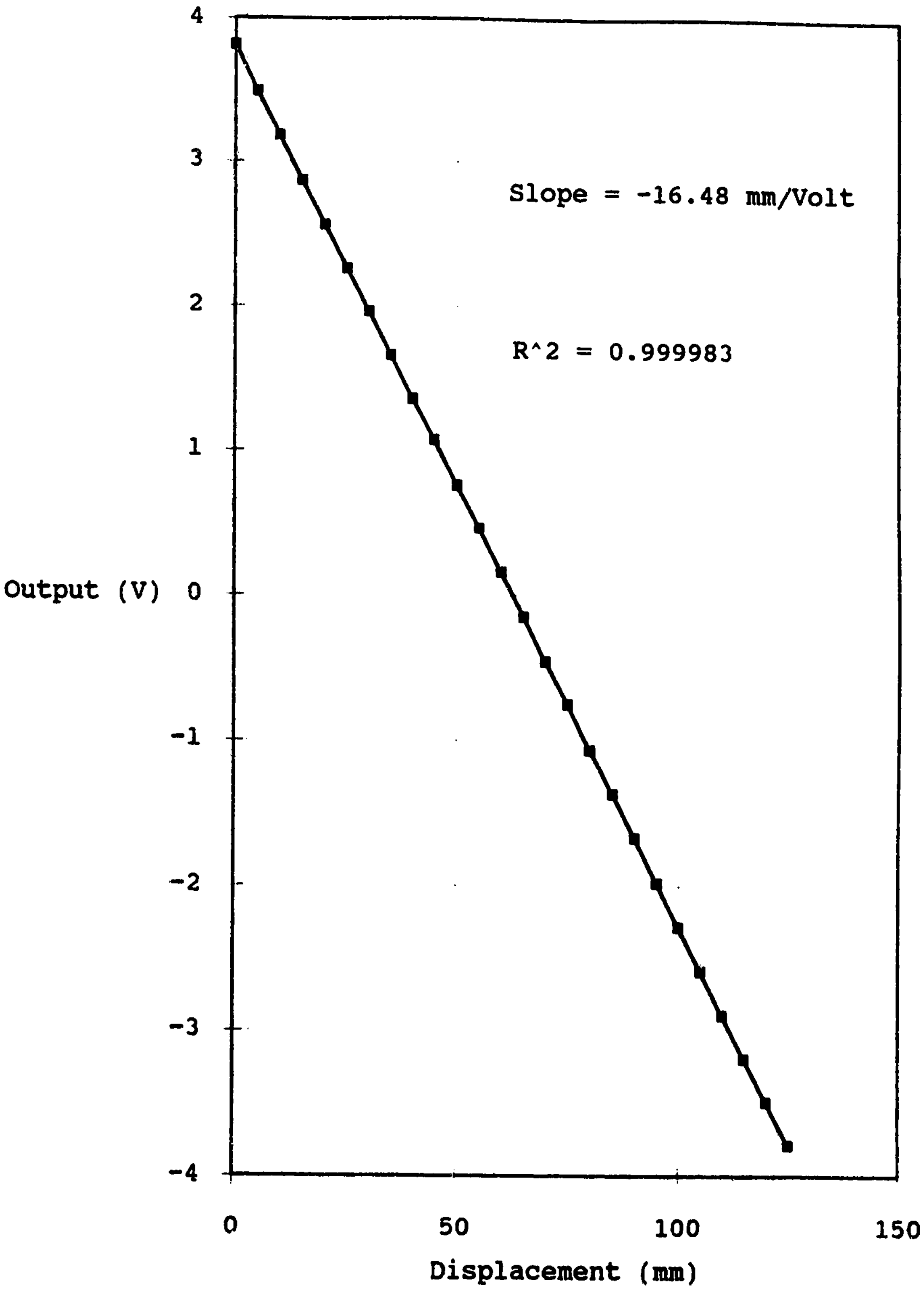


Figure A.4 Calibration of LVDT #2

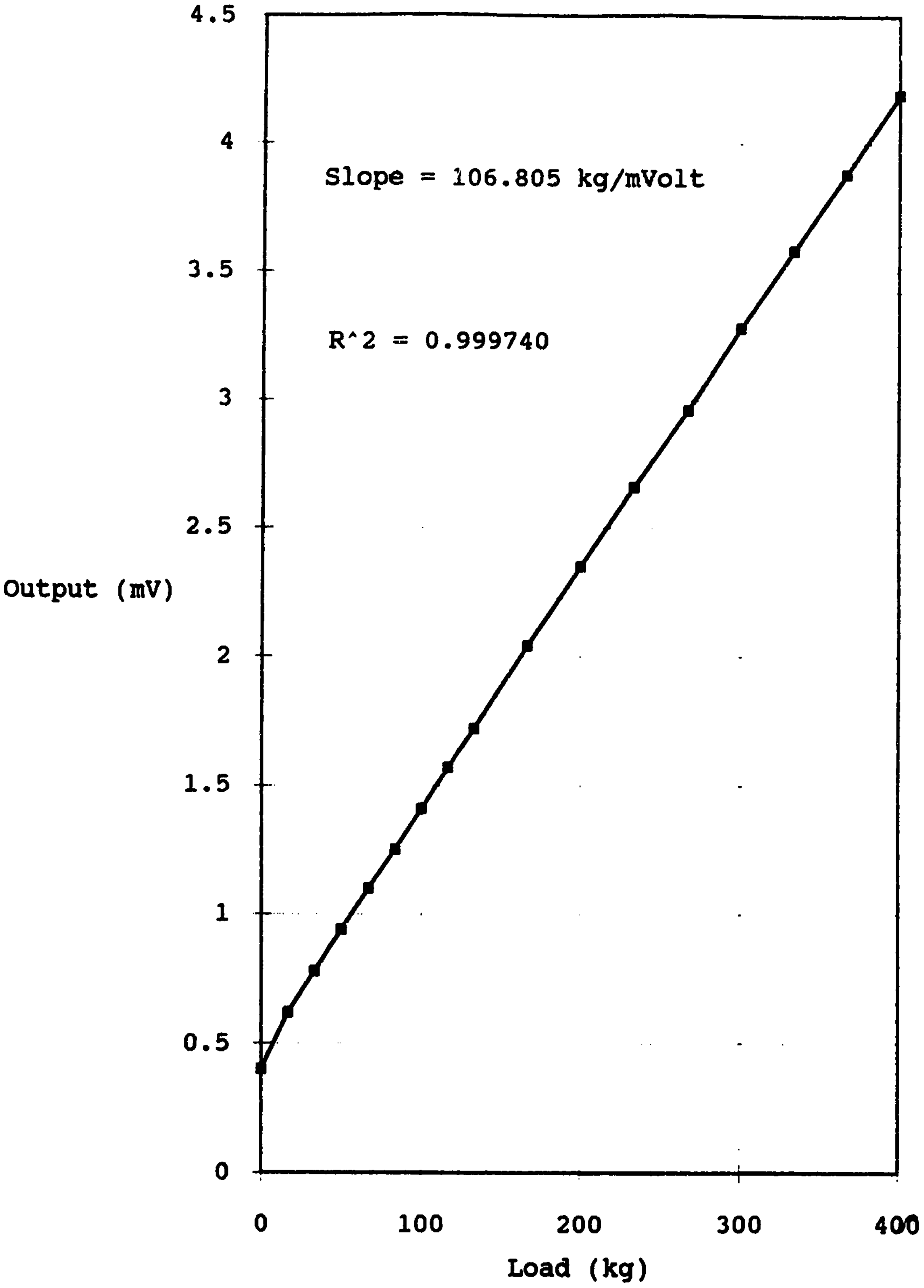


Figure A.5 Calibration of Load Cell #1

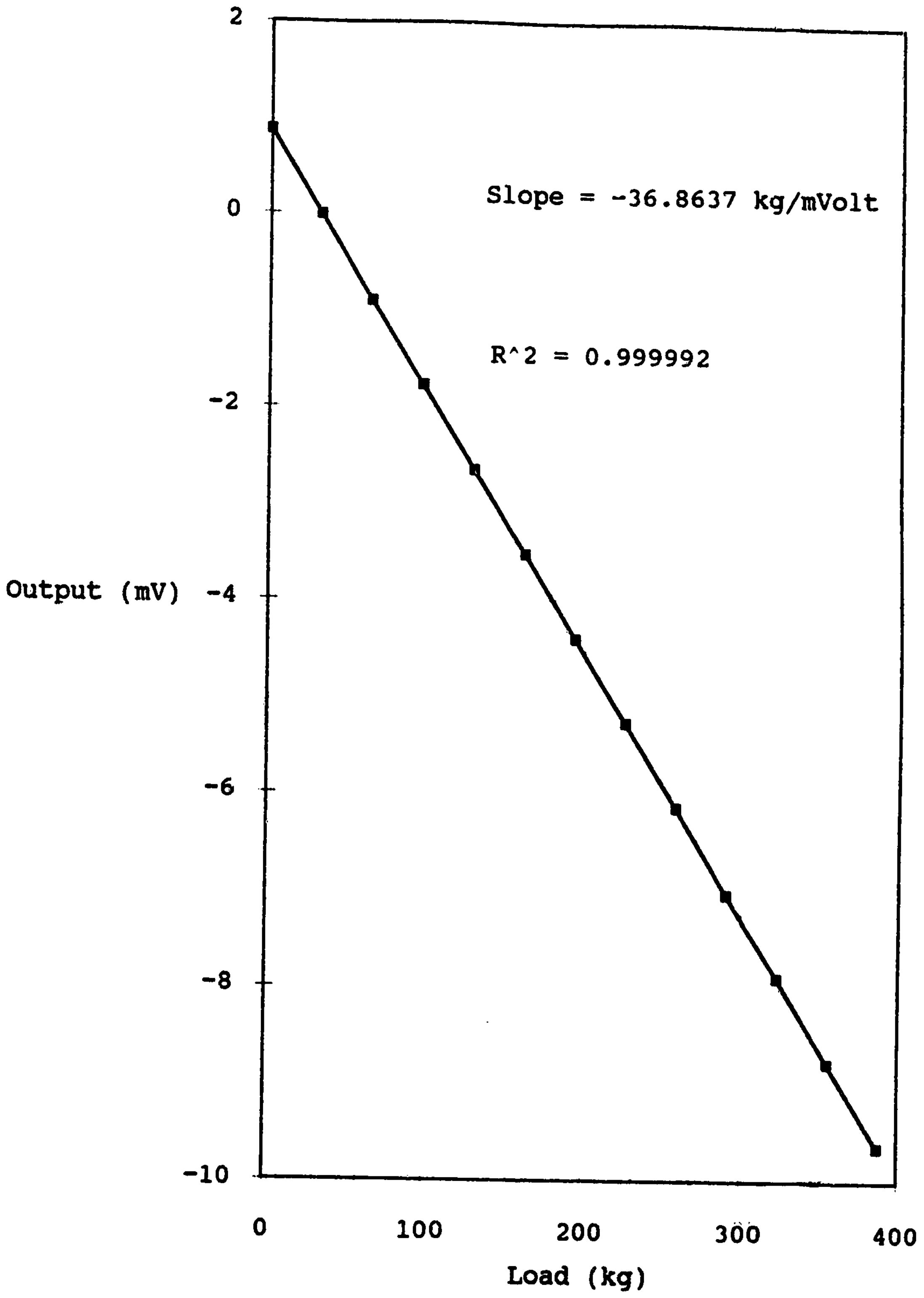


Figure A.6 Calibration of Load Cell #2

Appendix B - Consolidation Time Plots

The void ratio - time plots for the individual loads for the step load consolidation test on batch #1 tailings are presented in Figures B.1 to B.6. The individual plots for the step load test on batch #2 tailings are presented in Figures B.7 to B.14.

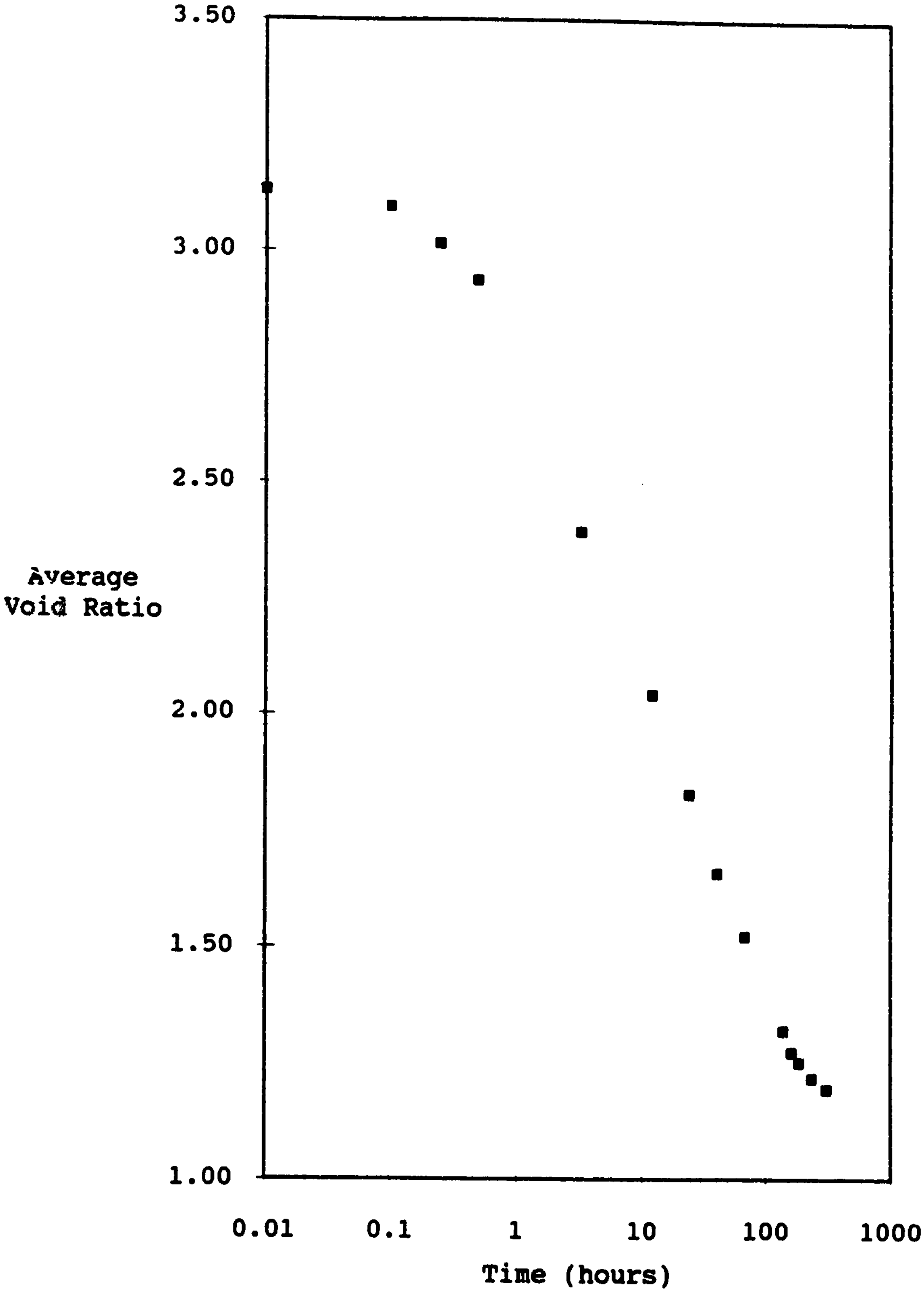


Figure B.1 Tailings Batch #1 - Step Load Consolidation - Self-Weight

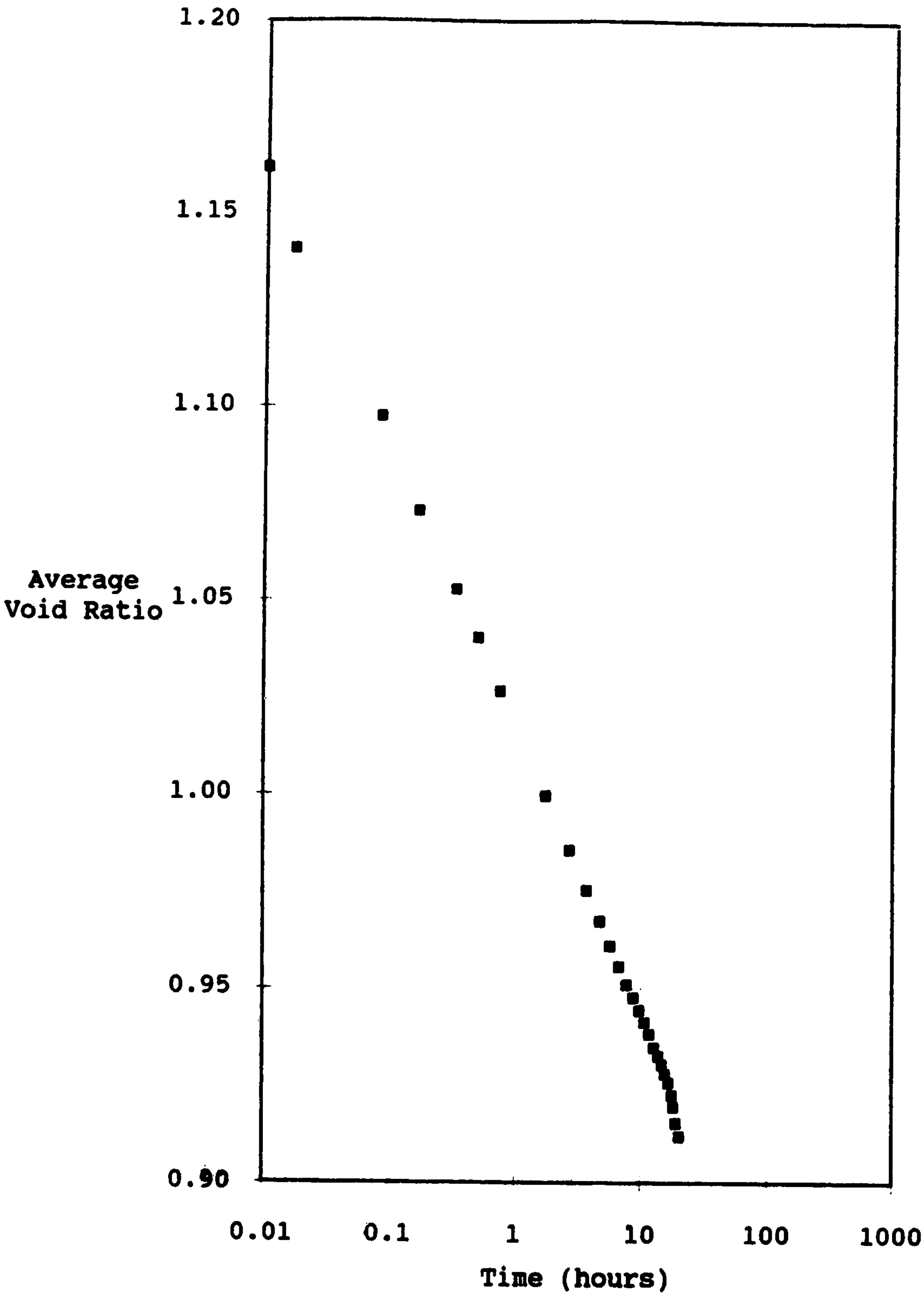


Figure B.2 Tailings Batch #1 - Step Load Consolidation - 2.5 kPa

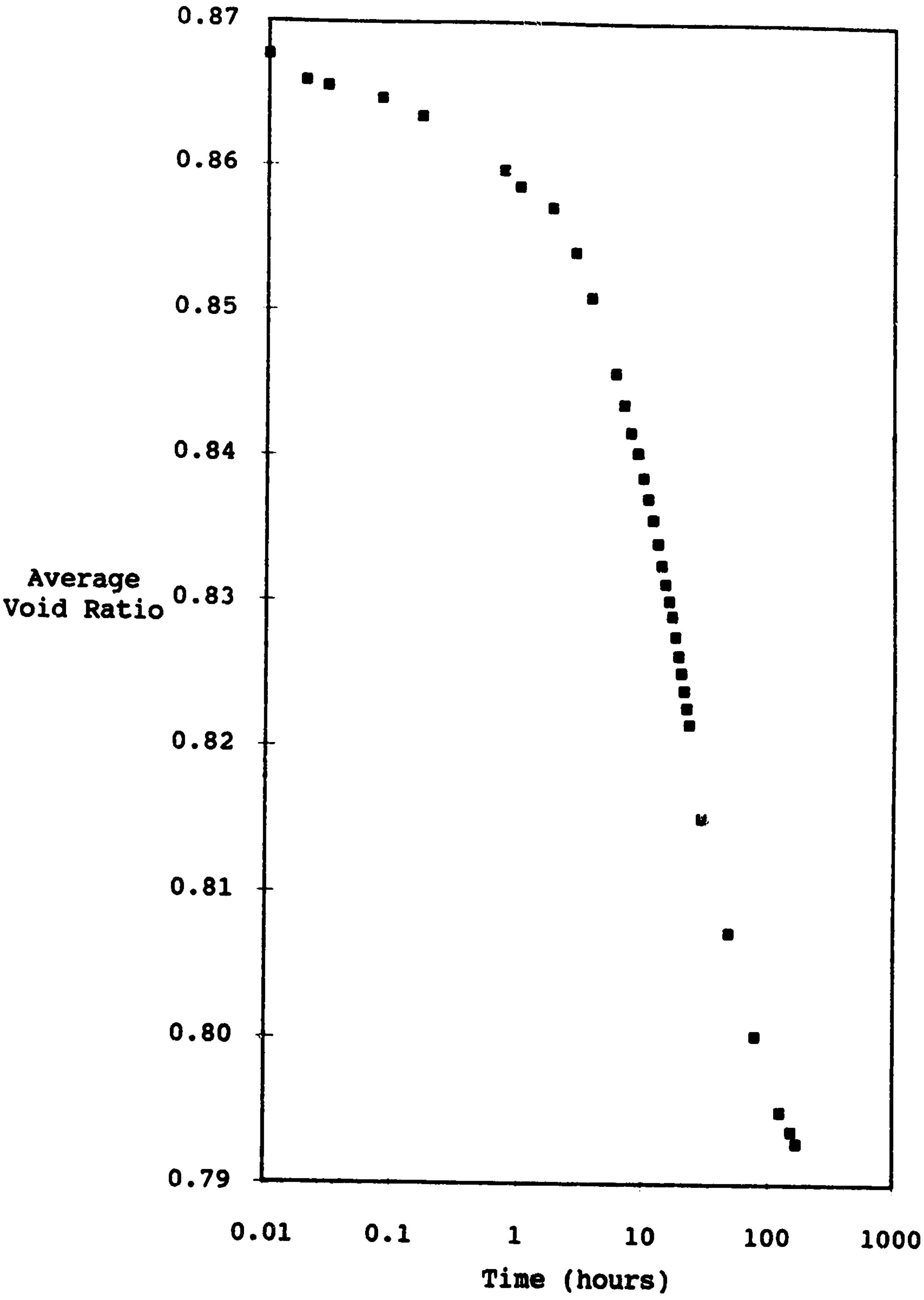


Figure B.3 Tailings Batch #1 - Step Load Consolidation - 5.0 kPa

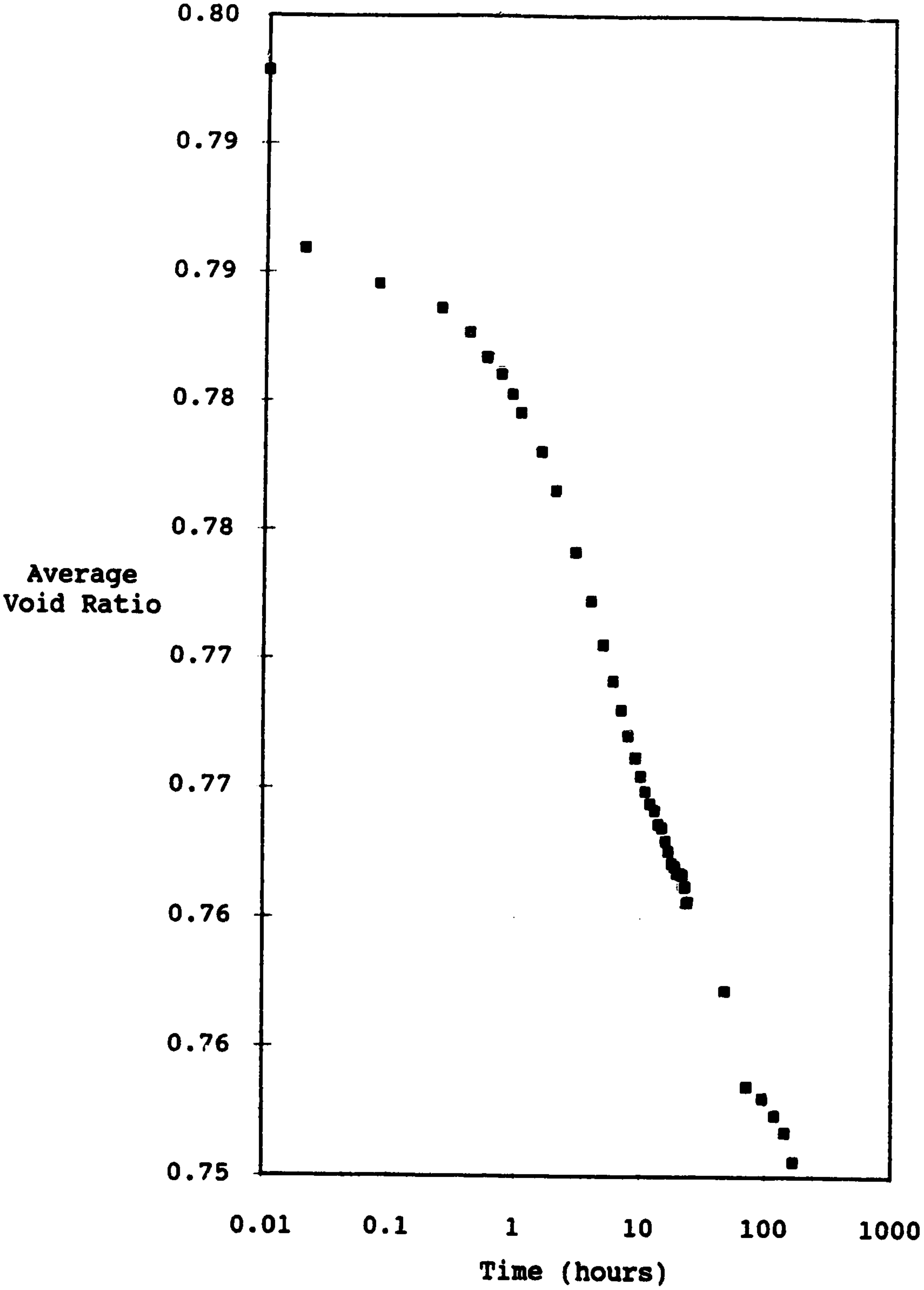


Figure B.4 Tailings Batch #1 - Step Load Consolidation - 10.0 kPa

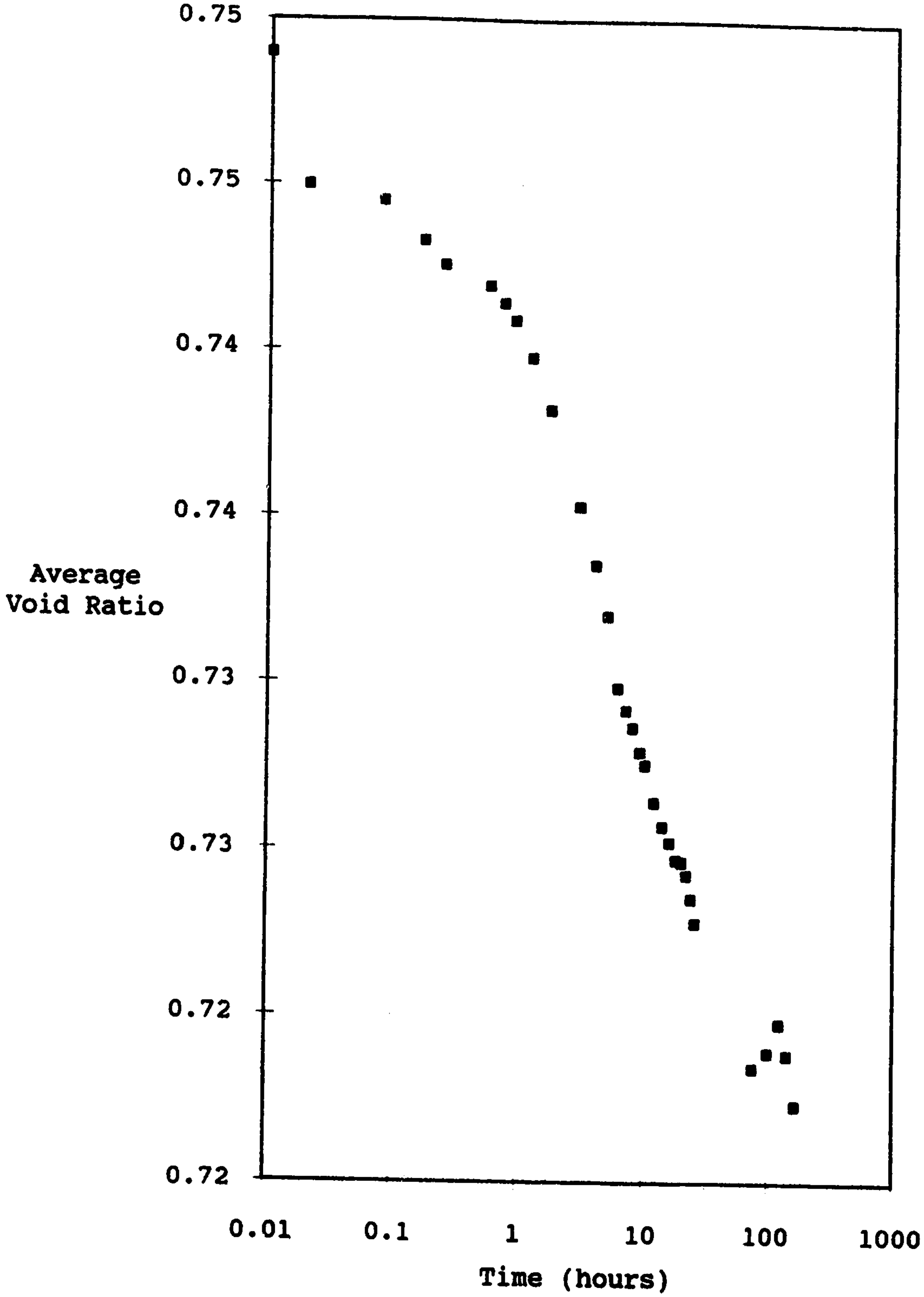


Figure B.5 Tailings Batch #1 - Step Load Consolidation - 20.0 kPa

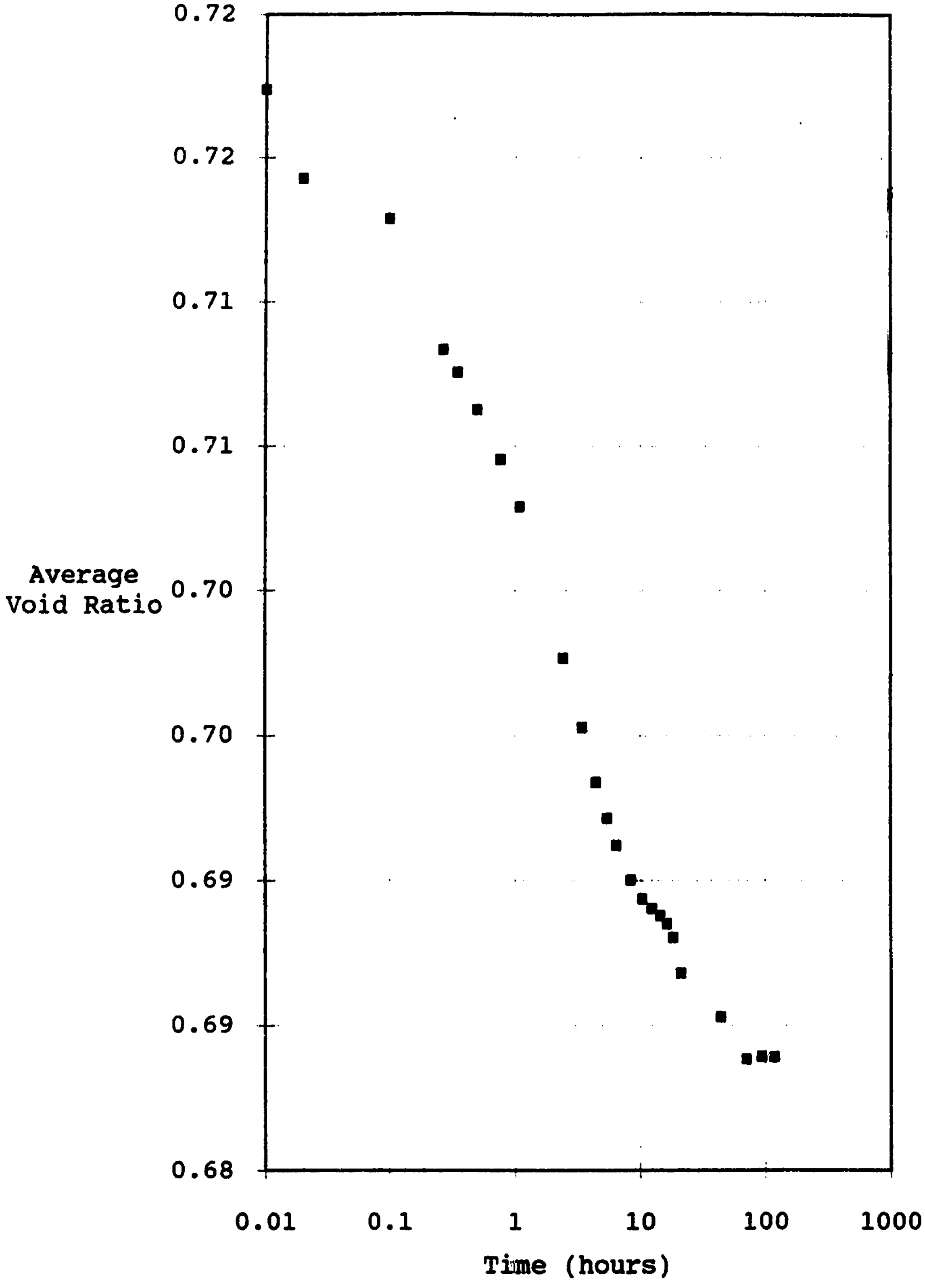


Figure B.6 Tailings Batch #1 - Step Load Consolidation - 40.0 kPa

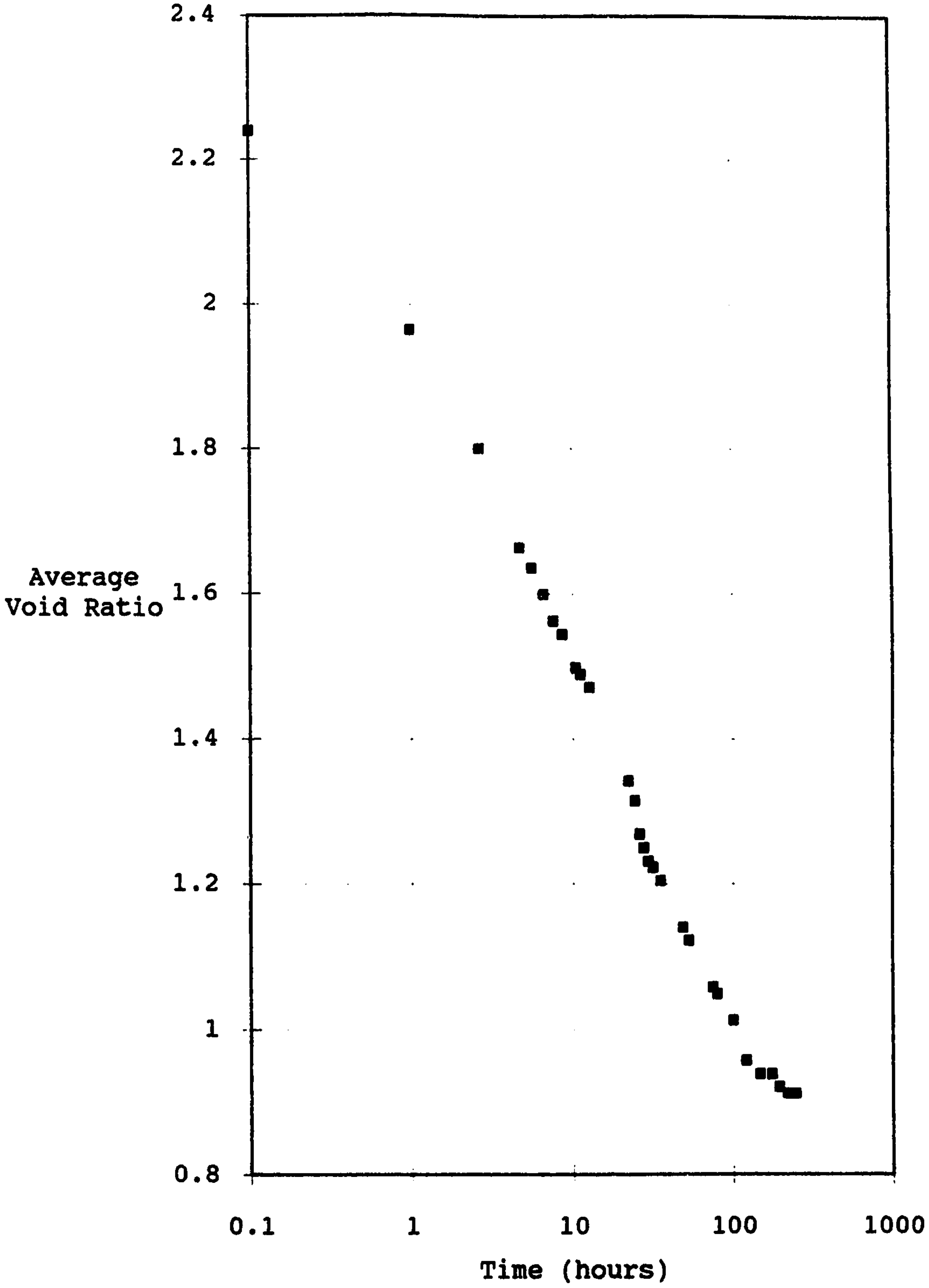


Figure B.7 Tailings Batch #2 - Step Load Consolidation - Self-Weight

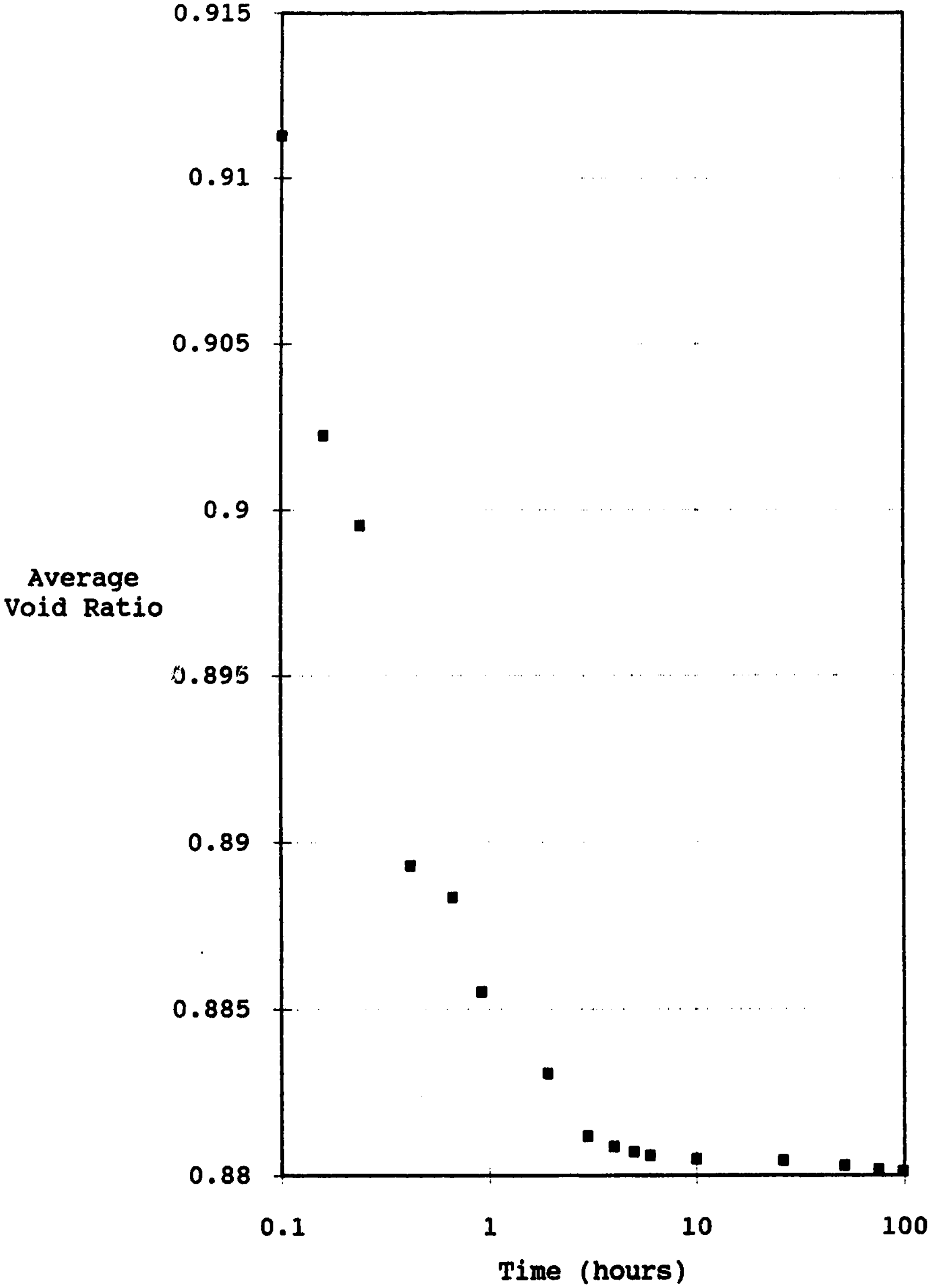


Figure B.8 Tailings Batch #2 - Step Load Consolidation - 1.25 kPa

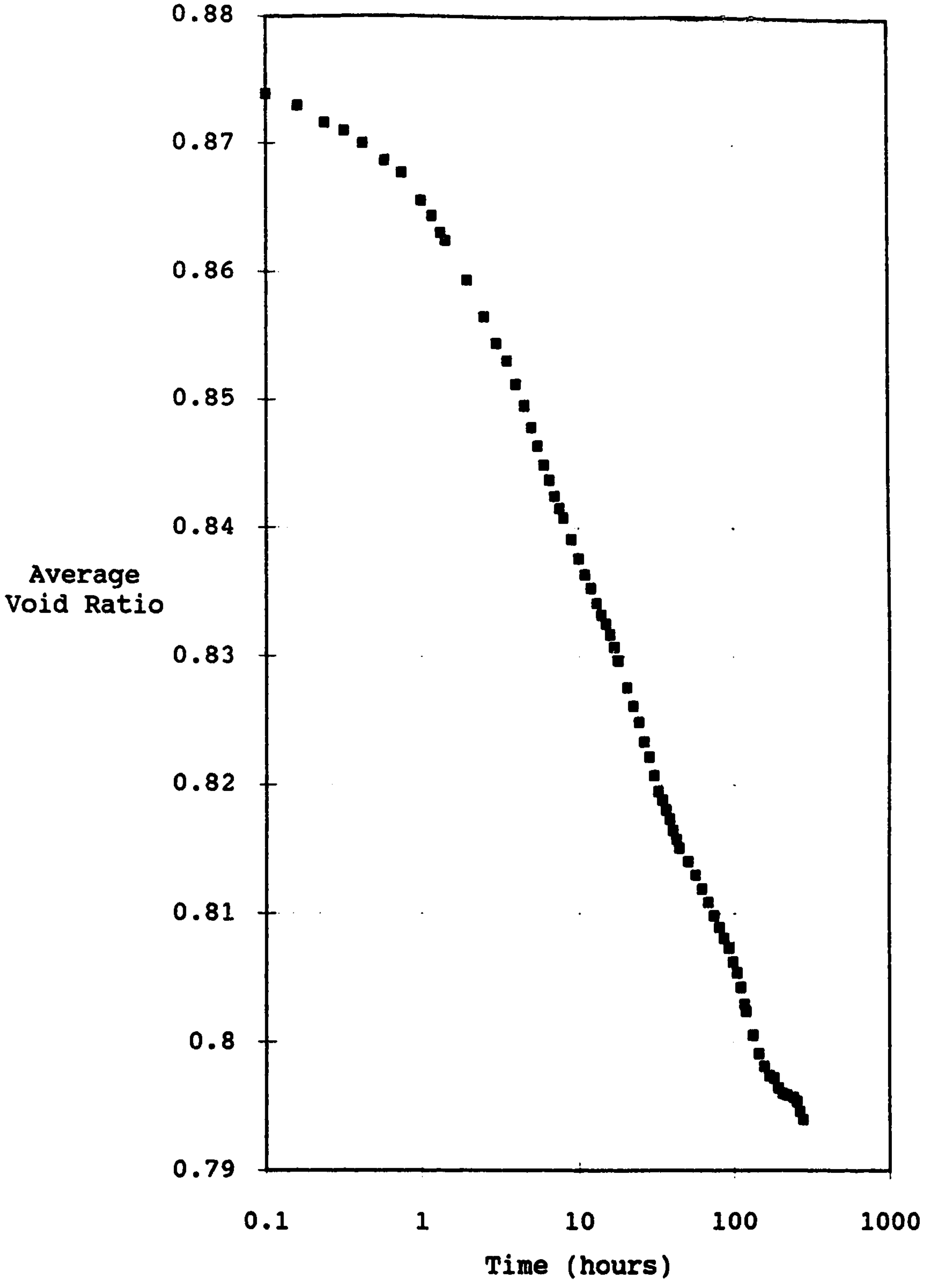


Figure B.9 Tailings Batch #2 - Step Load Consolidation - 2.5 kPa

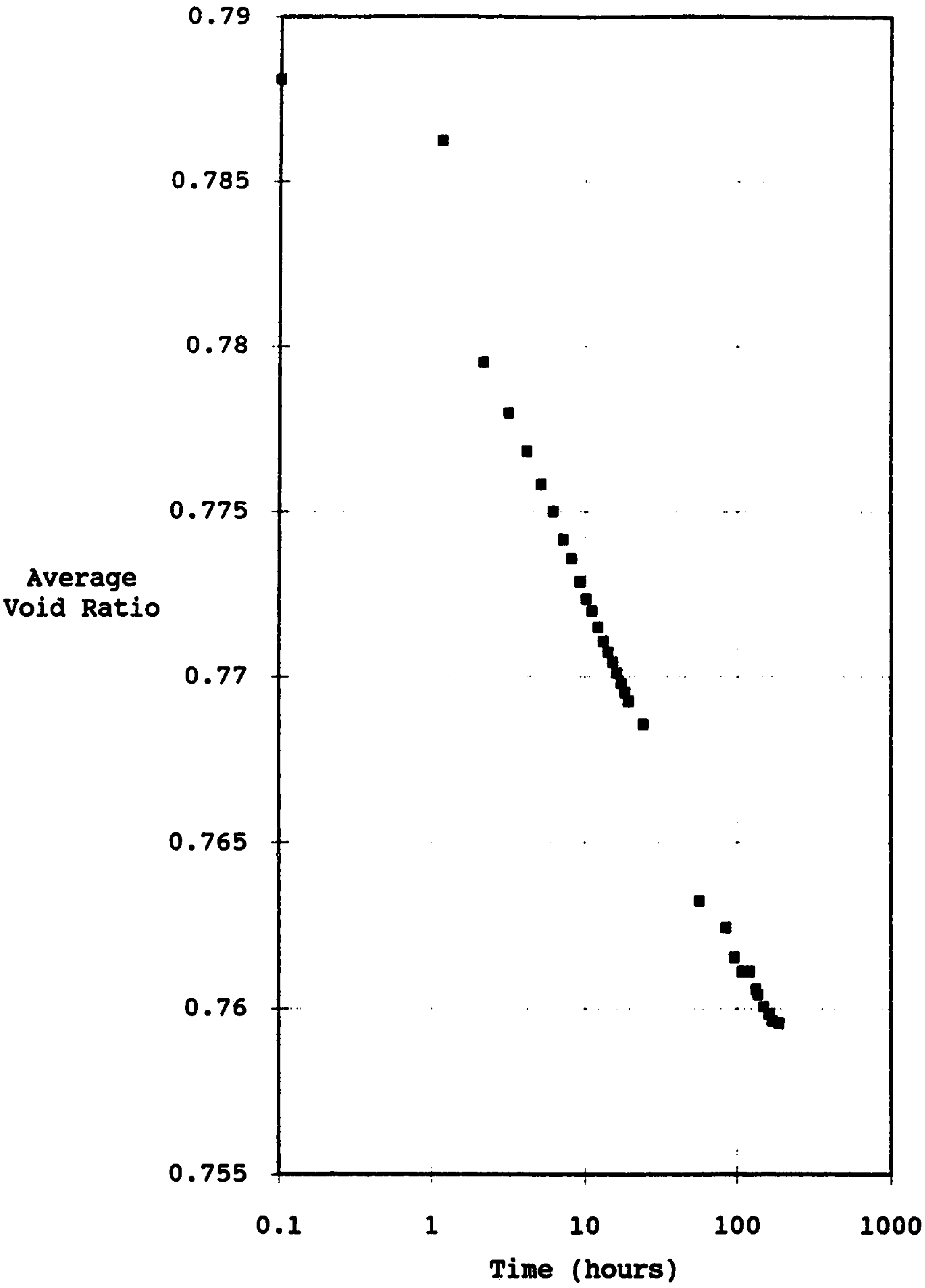


Figure B.10 Tailings Batch #2 - Step Load Consolidation - 5.0 kPa

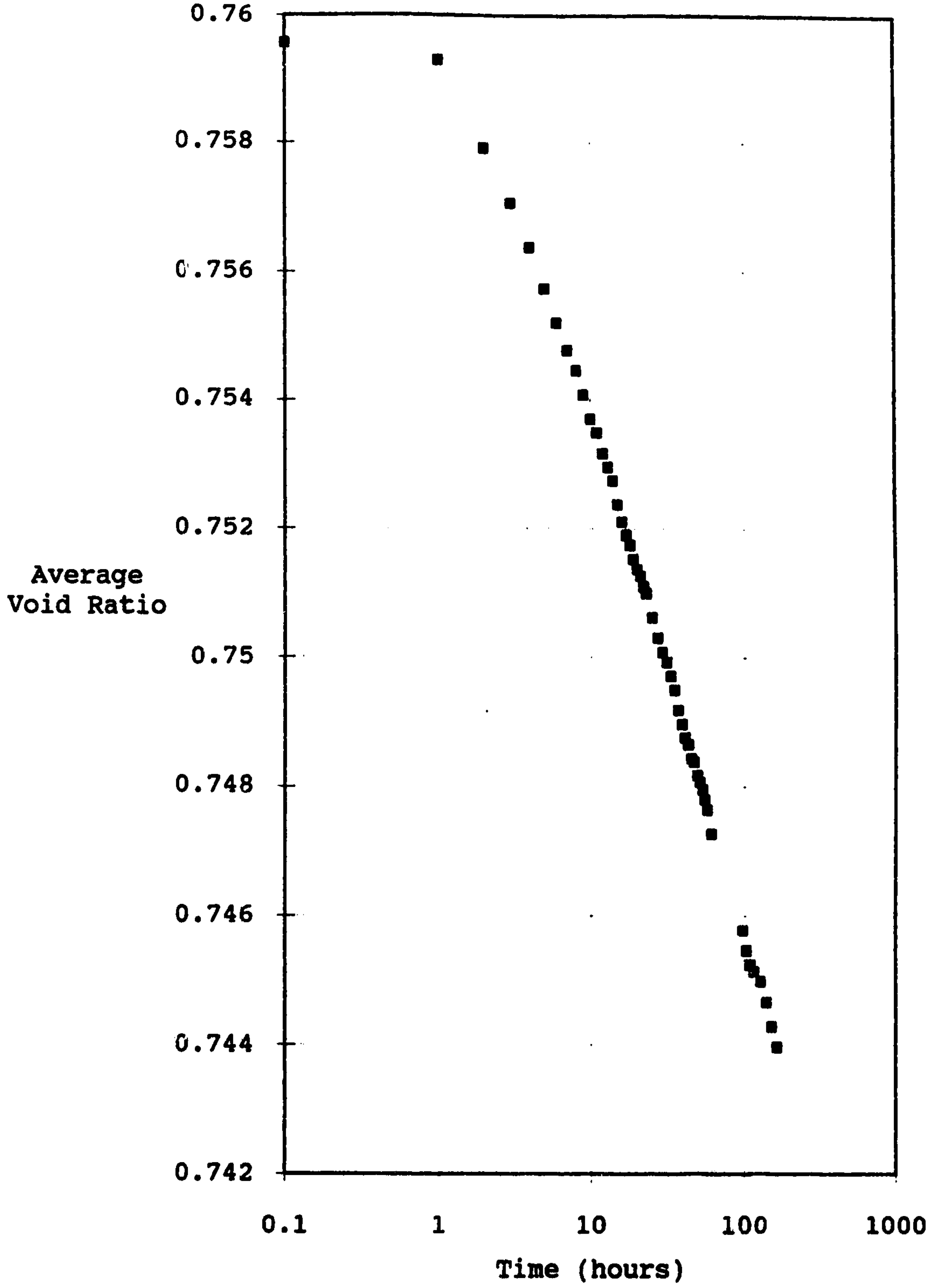


Figure B.11 Tailings Batch #2 - Step Load Consolidation - 10.0 kPa

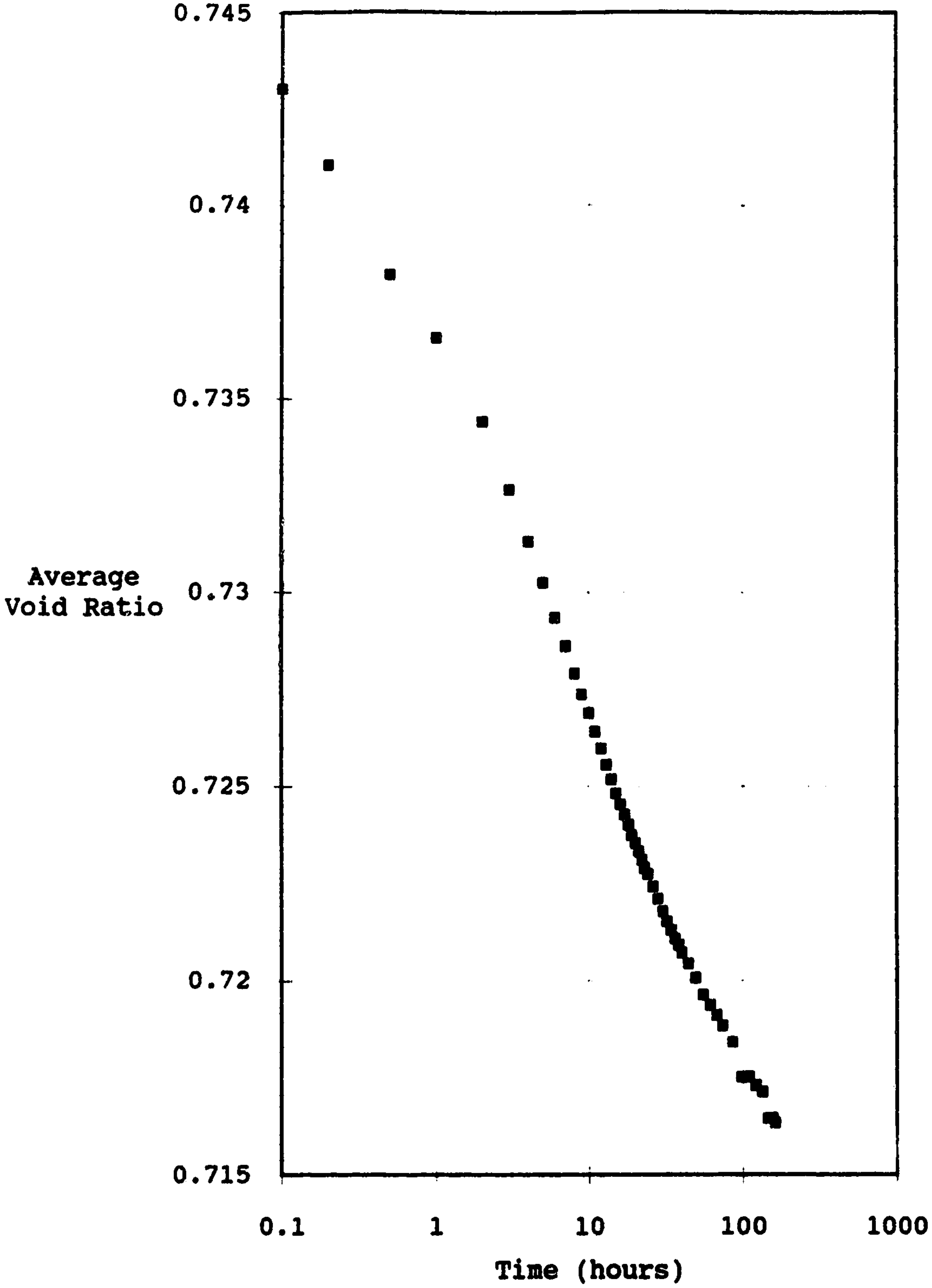


Figure B.12 Tailings Batch #2 - Step Load Consolidation - 20.0 kPa

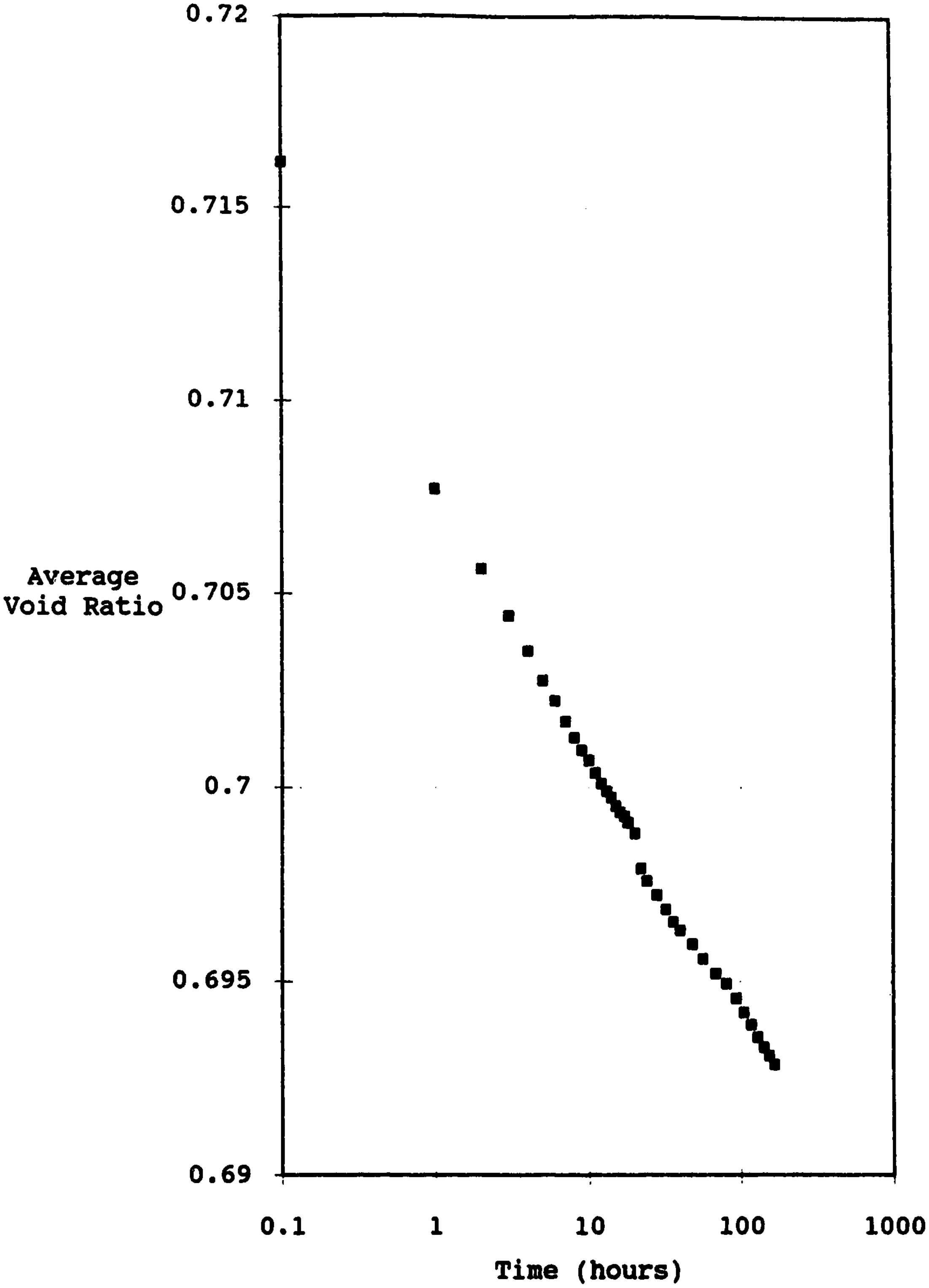


Figure B.13 Tailings Batch #2 - Step Load Consolidation - 40.0 kPa

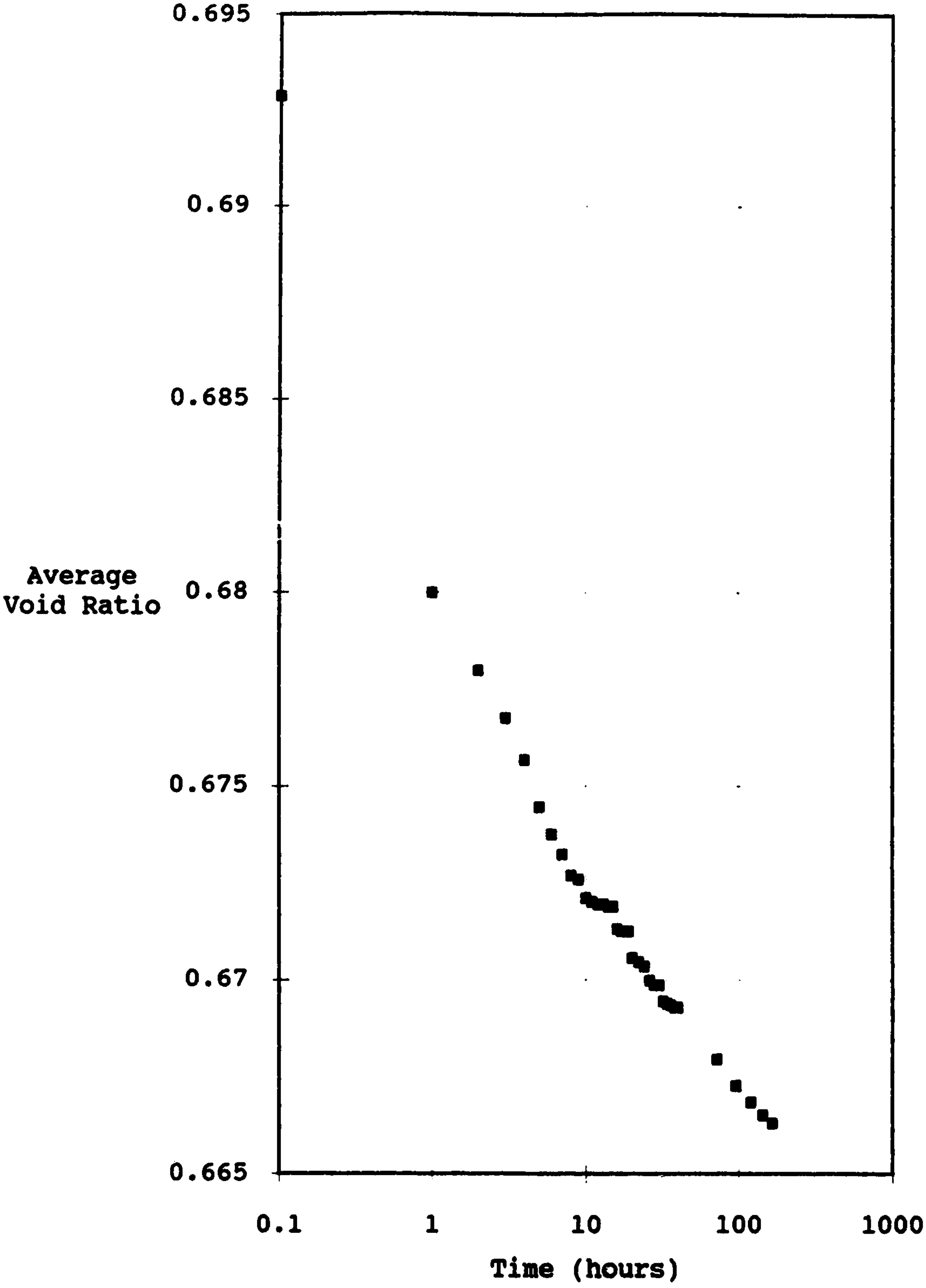


Figure B.14 Tailings Batch #2 - Step Load Consolidation - 80.0 kPa

Appendix C - Pore Pressure Plots

The plots of excess pore pressure for each load of the step load test on batch #1 tailings are presented in Figures C.1 to C.6. The excess pore pressure plot for the constant rate of deformation test on batch #1 tailings is in Figure C.7.

The excess pore pressure versus time plots for the step load test on batch #2 tailings are presented in Figures C.8 to C.14. Plots of excess pore pressure versus total stress for the constant rate of deformation tests on batch #2 tailings are in Figures C.15 to C.17. The plots of the ratio of excess pore pressure to total stress versus void ratio for the same tests are in Figures C.18 to C.20.

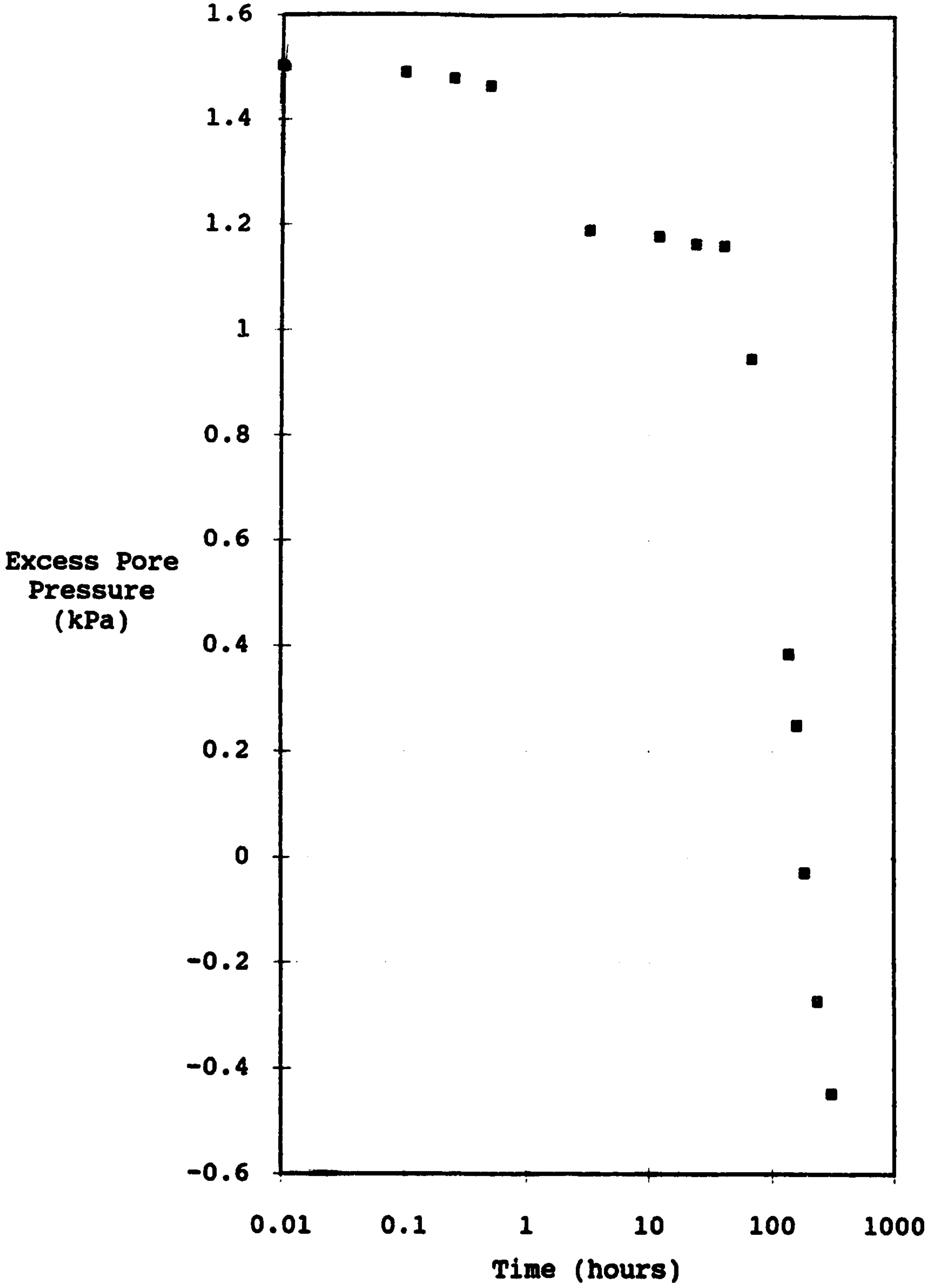


Figure C.1 Excess Pore Pressure - Batch #1 CLT - Self-Weight

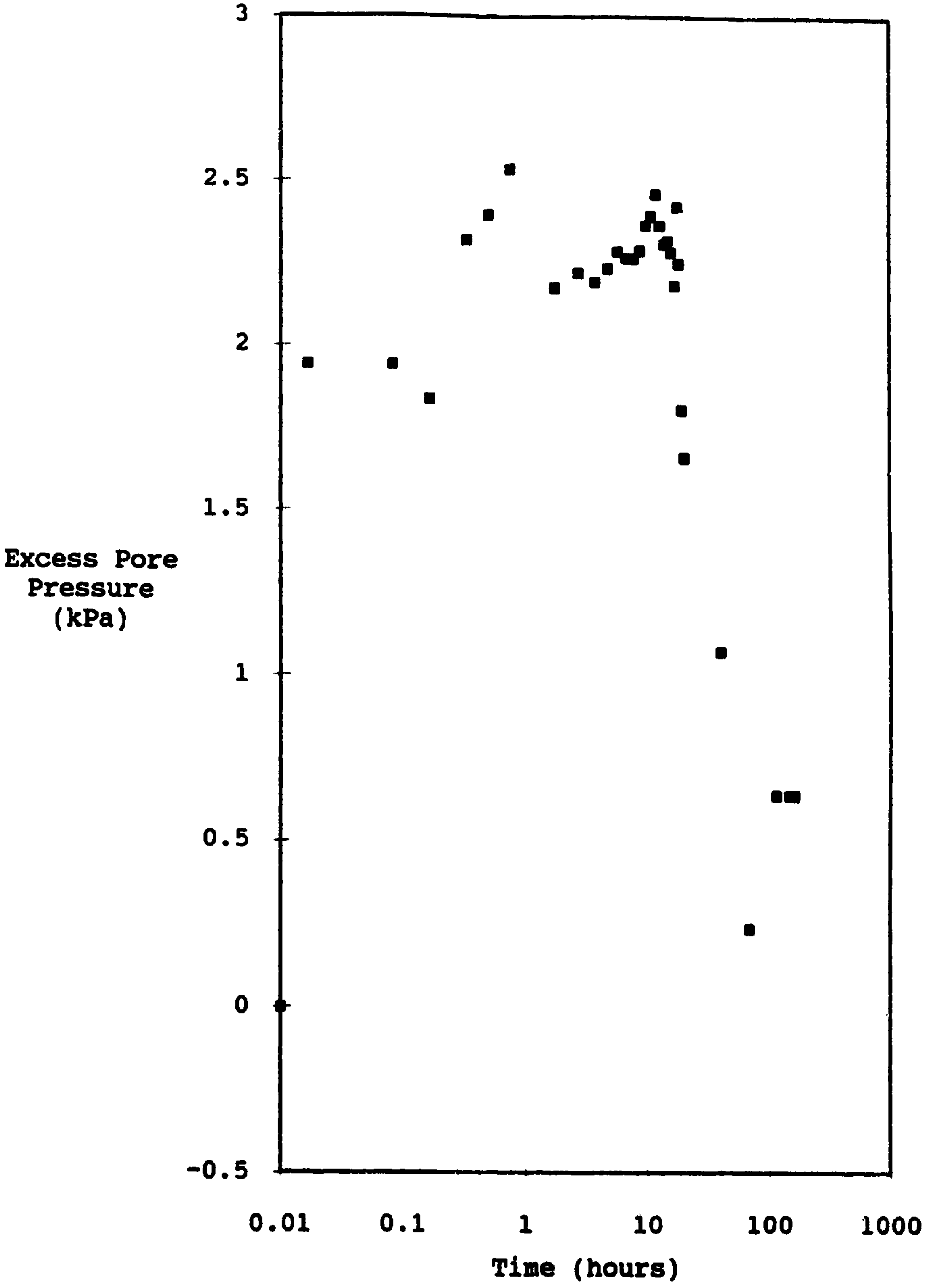


Figure C.2 Excess Pore Pressure - Batch #1 CLT - 2.5 kPa Total Stress

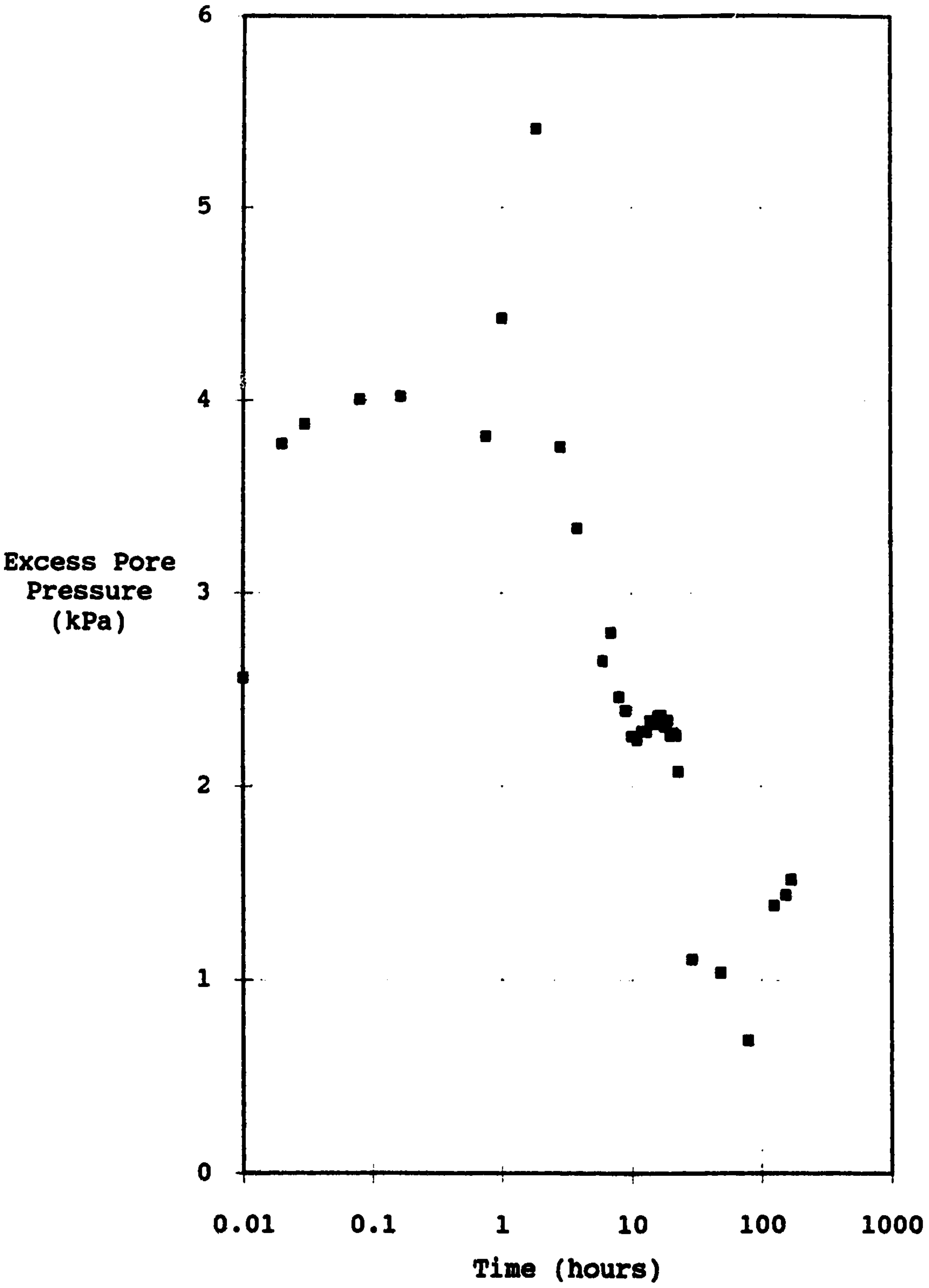


Figure C.3 Excess Pore Pressure - Batch #1 CLT - 5.0 kPa Total Stress (2.5 kPa excess stress)

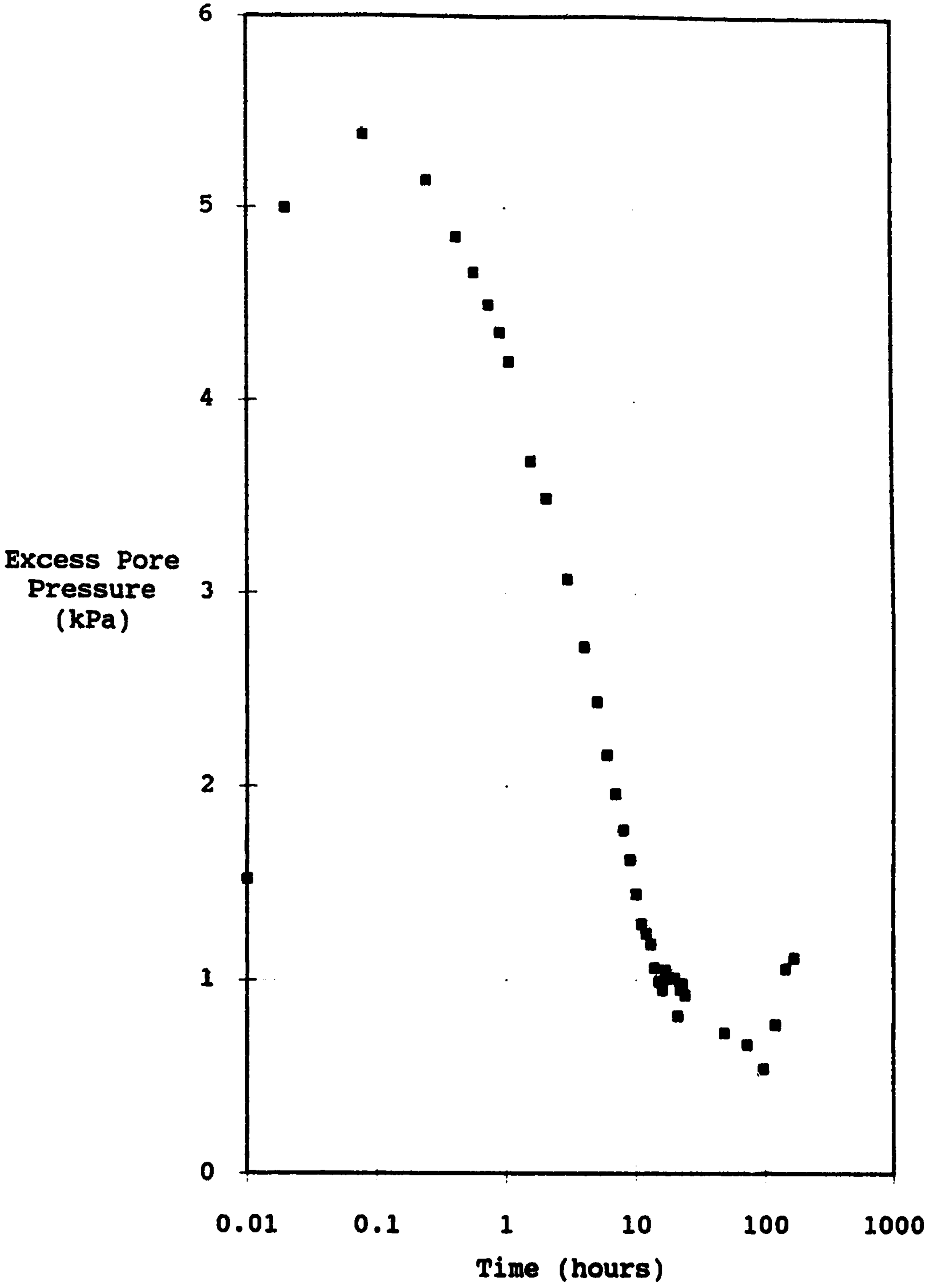


Figure C.4 Excess Pore Pressure - Batch #1 CLT - 10.0 kPa Total Stress (5 kPa excess stress)

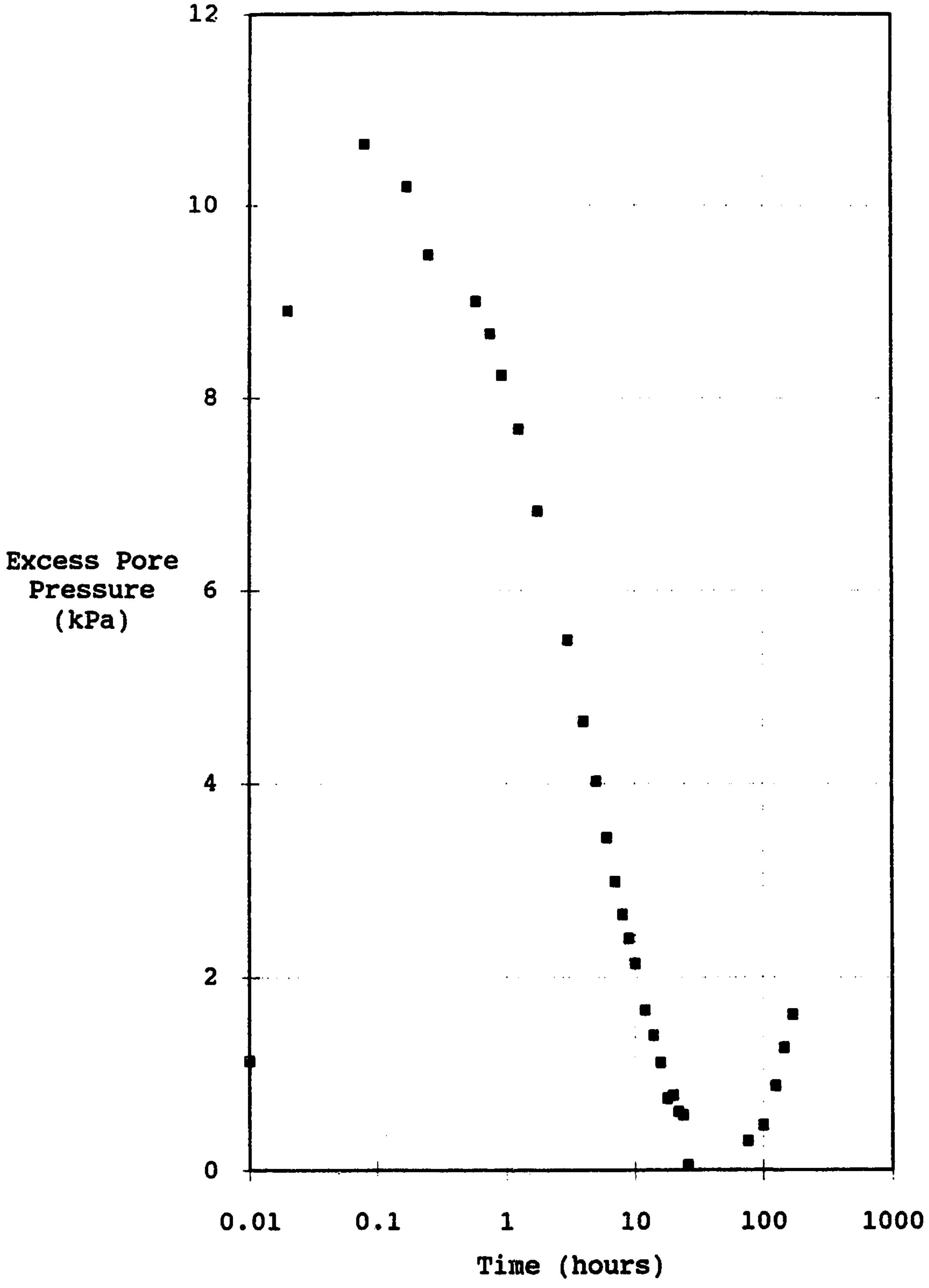


Figure C.5 Excess Pore Pressure - Batch #1 CLT - 20.0 kPa Total Stress (10 kPa excess stress)

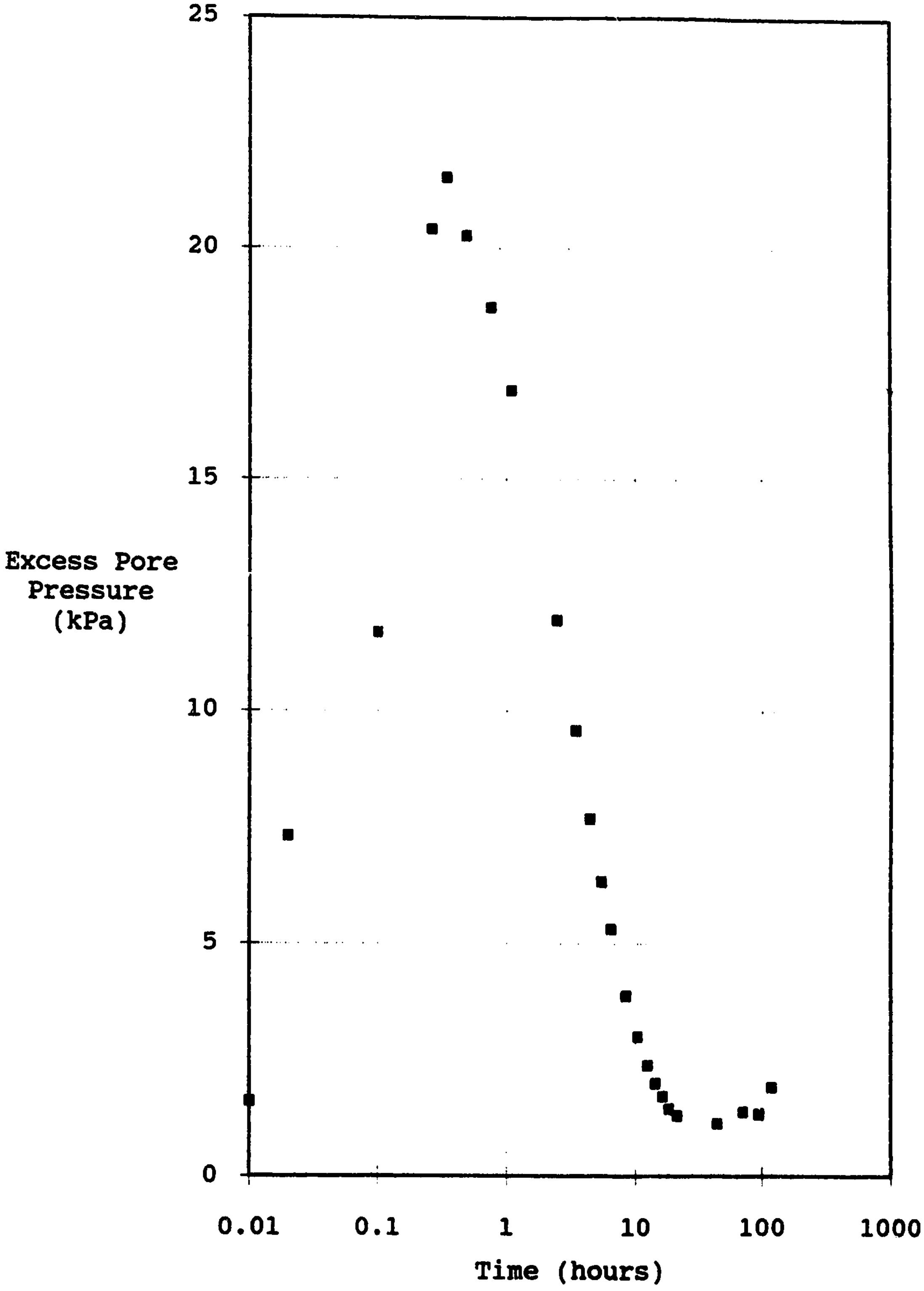


Figure C.6 Excess Pore Pressure - Batch #1 CLT - 40.0 kPa Total Stress (20 kPa excess stress)

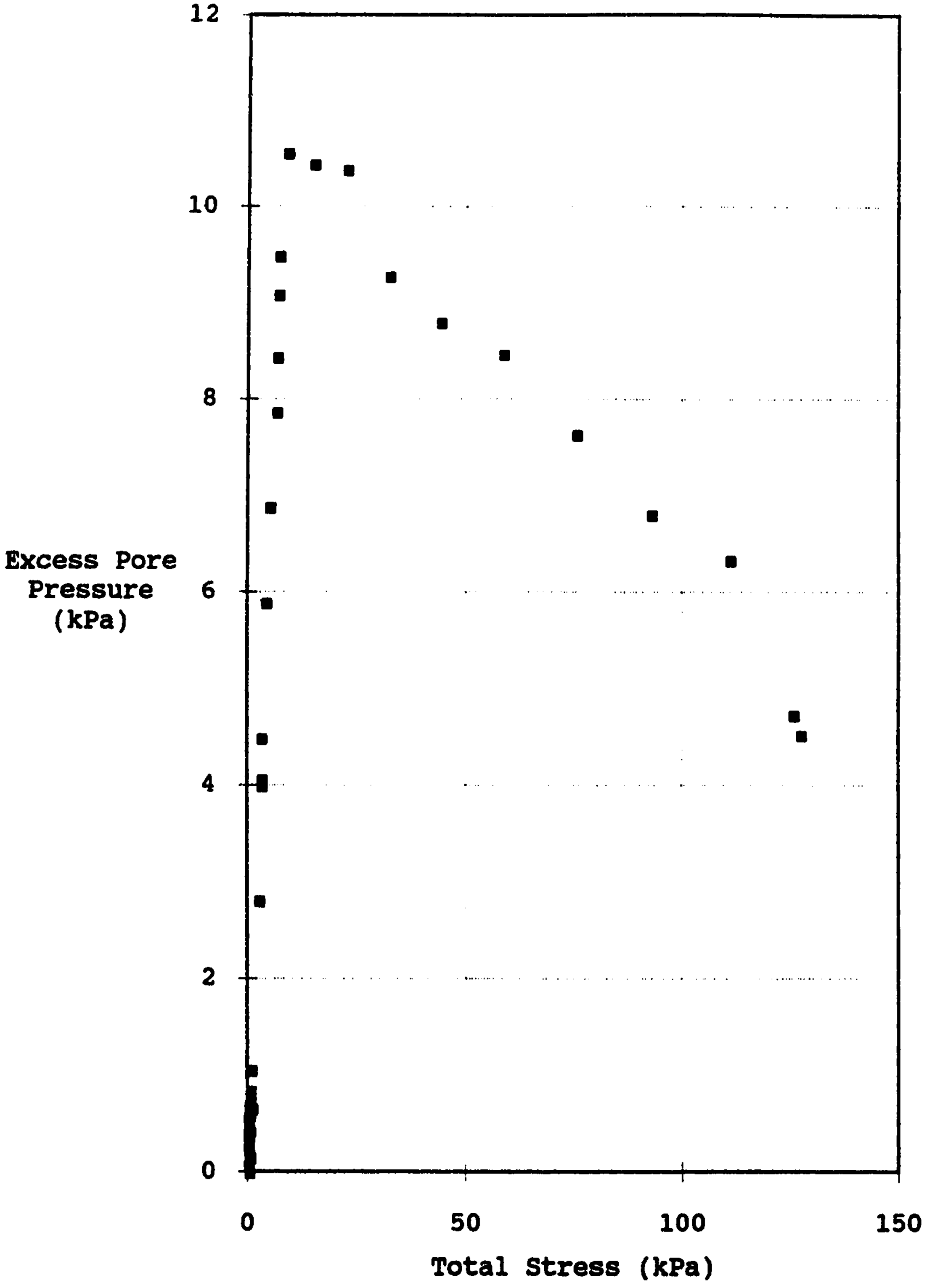


Figure C.7 Tailings Batch #1 - Constant Rate of Deformation Test - Excess Pore Pressure Plot

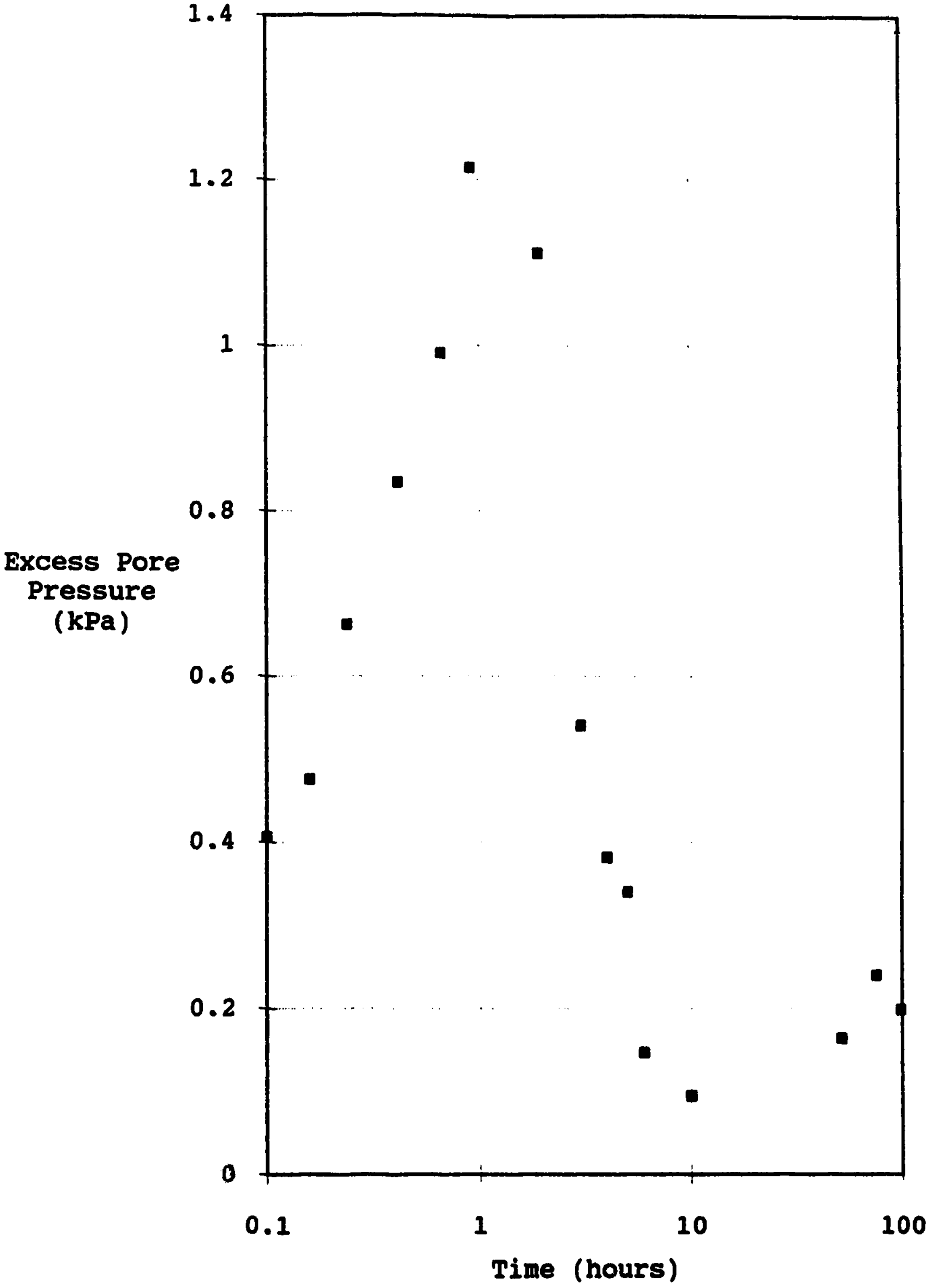


Figure C.8 Excess Pore Pressure - Batch #2 CLT - 1.25 kPa Total Stress

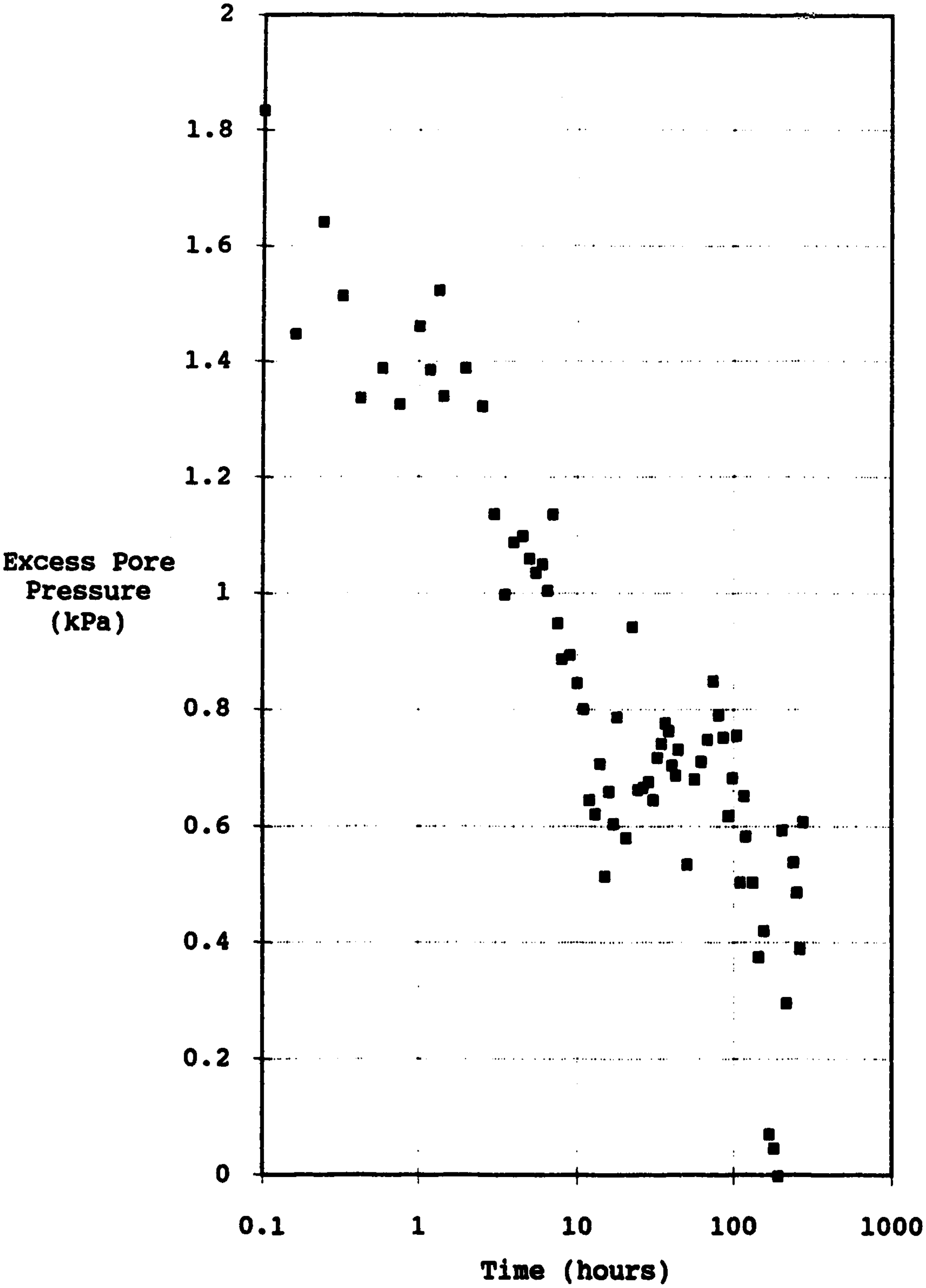


Figure C.9 Excess Pore Pressure - Batch #2 CLT - 2.5 kPa Total Stress (1.25 kPa excess stress)

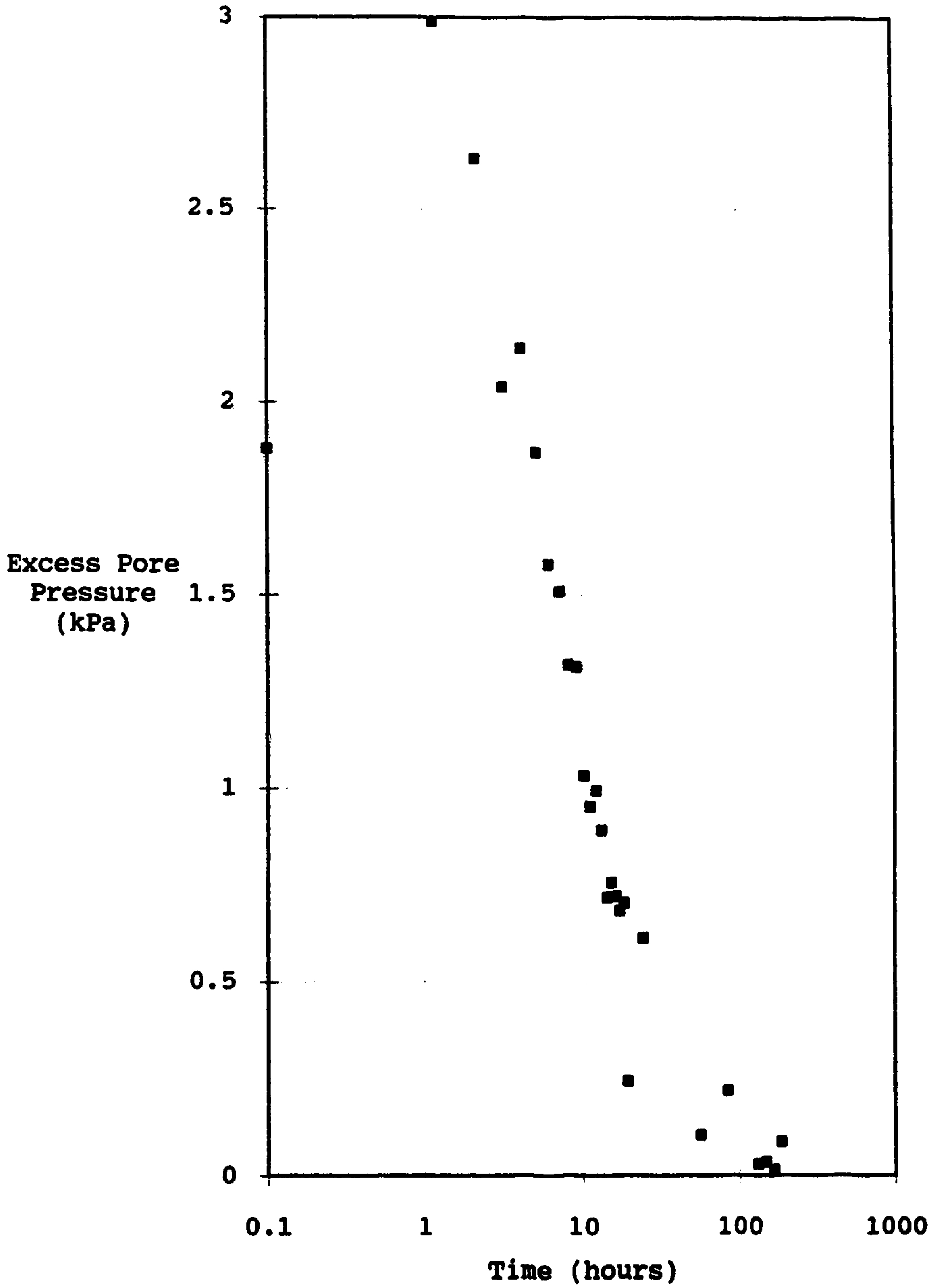


Figure C.10 Excess Pore Pressure - Batch #2 CLT - 5.0 kPa Total Stress (2.5 kPa excess stress)

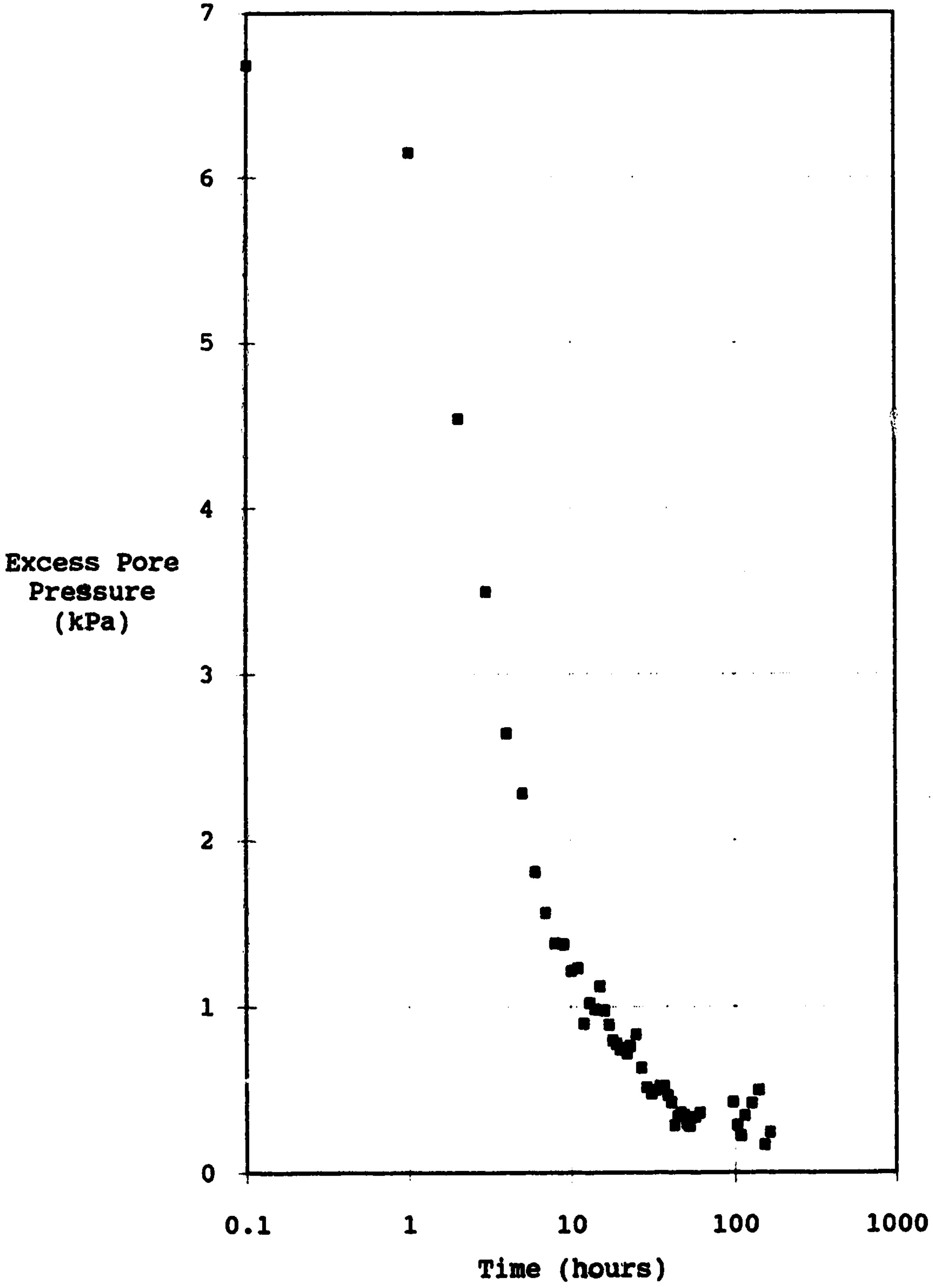


Figure C.11 Excess Pore Pressure - Batch #2 CLT - 10.0 kPa Total Stress (5 kPa excess stress)

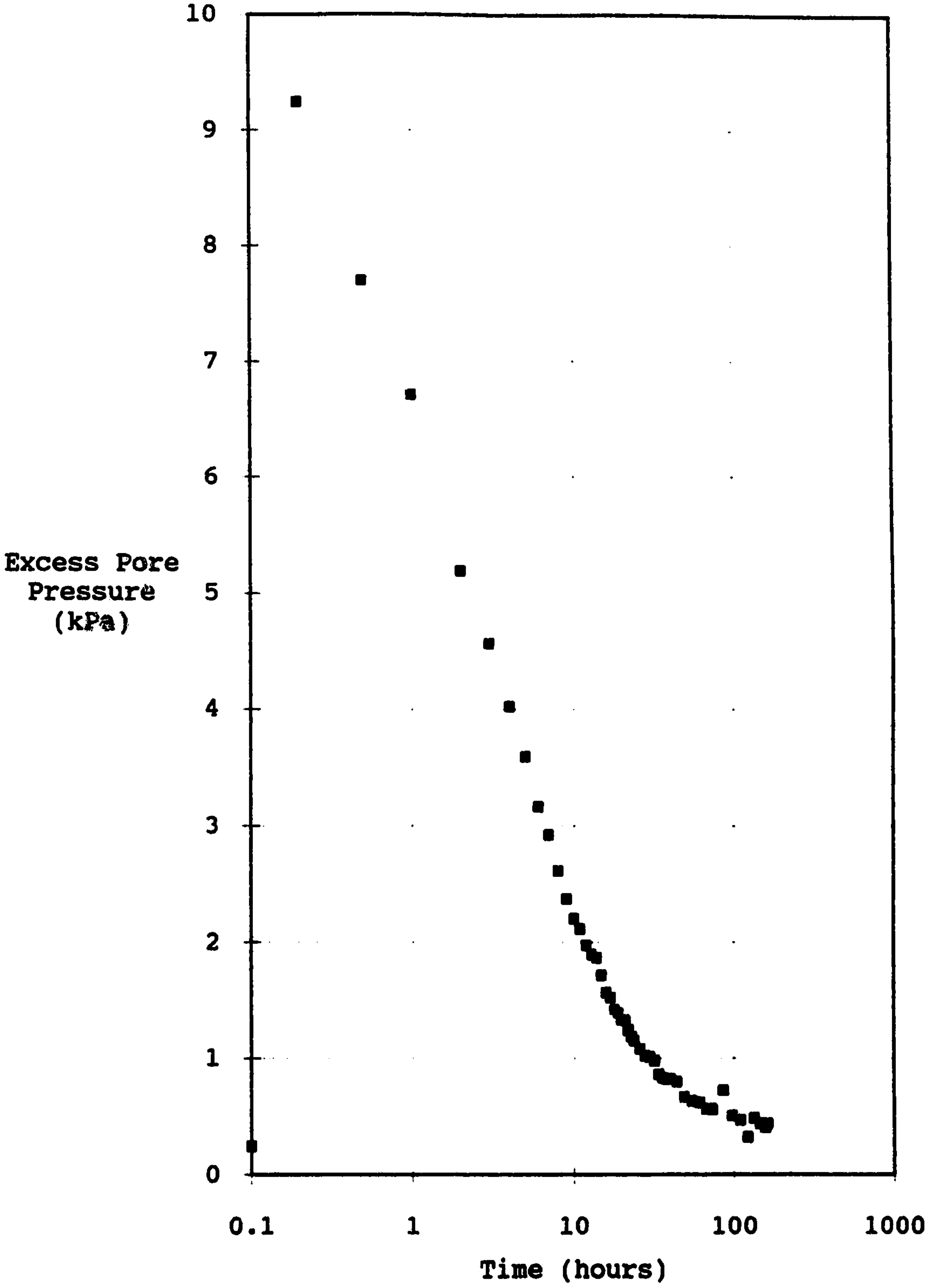


Figure C.12 Excess Pore Pressure - Batch #2 CLT - 20.0 kPa Total Stress (10 kPa excess stress)

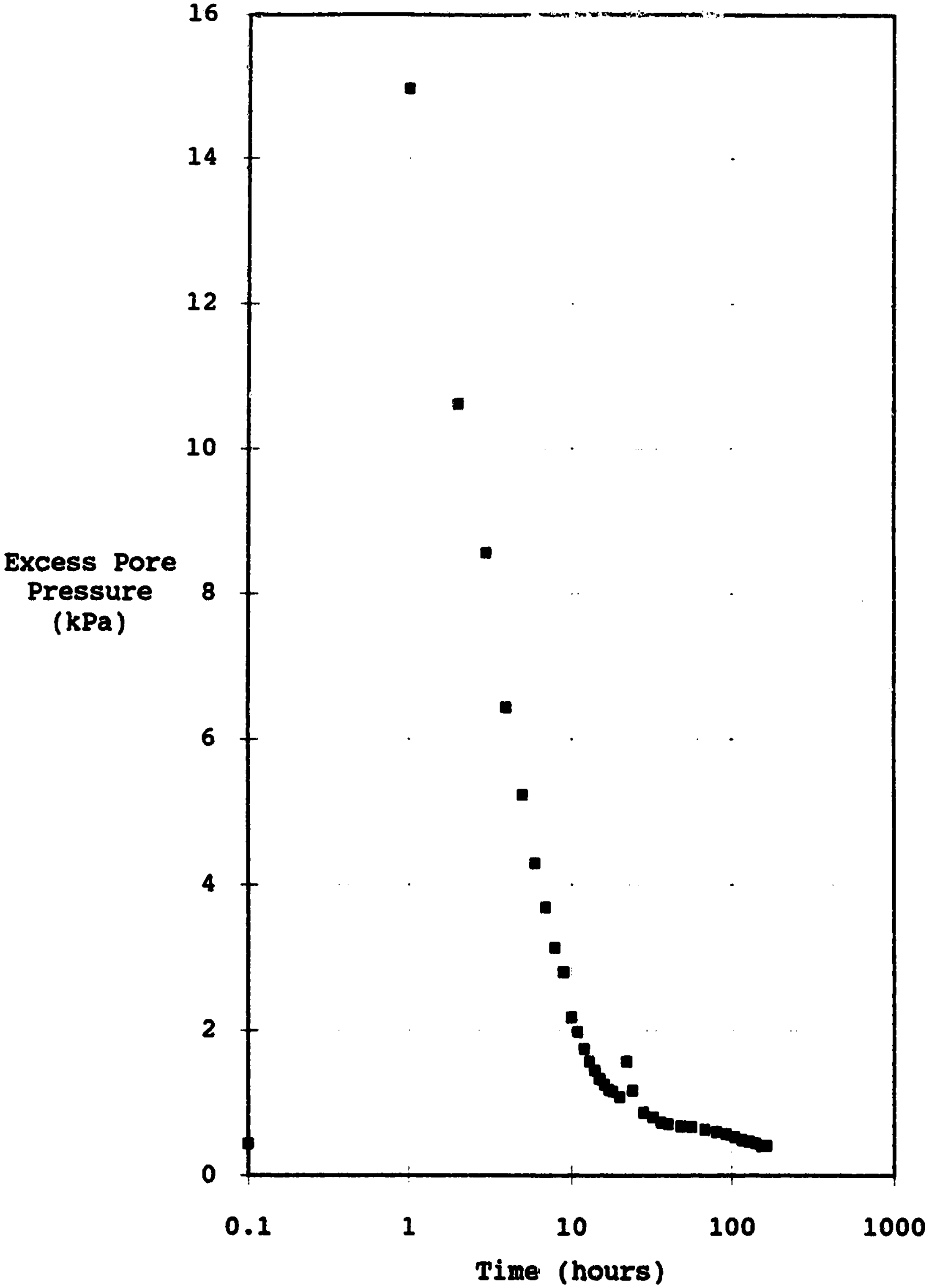


Figure C.13 Excess Pore Pressure - Batch #2 CLT - 40.0 kPa Total Stress (20 kPa excess stress)

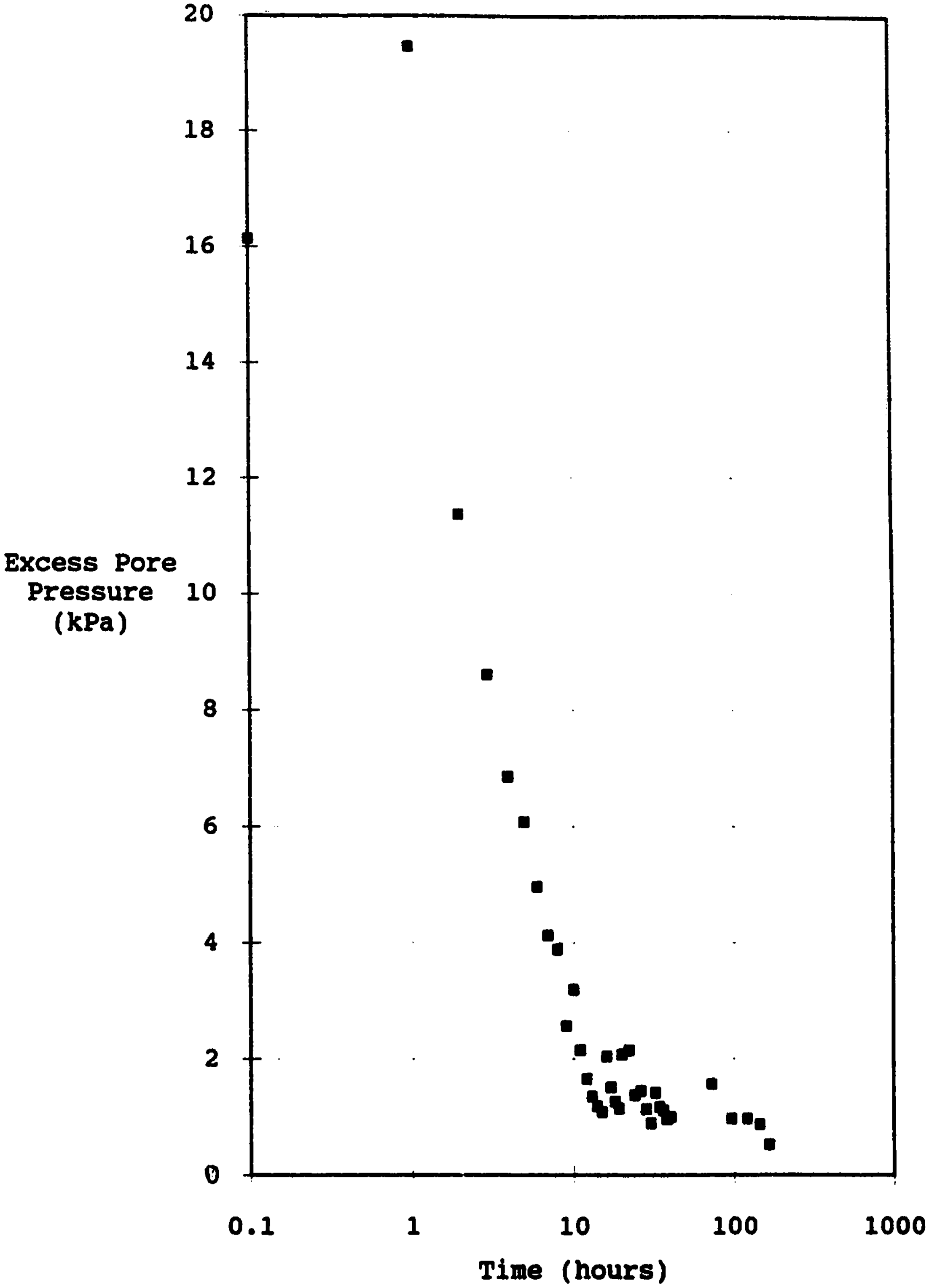


Figure C.14 Excess Pore Pressure - Batch #2 CLT - 80.0 kPa Total Stress (40 kPa excess stress)

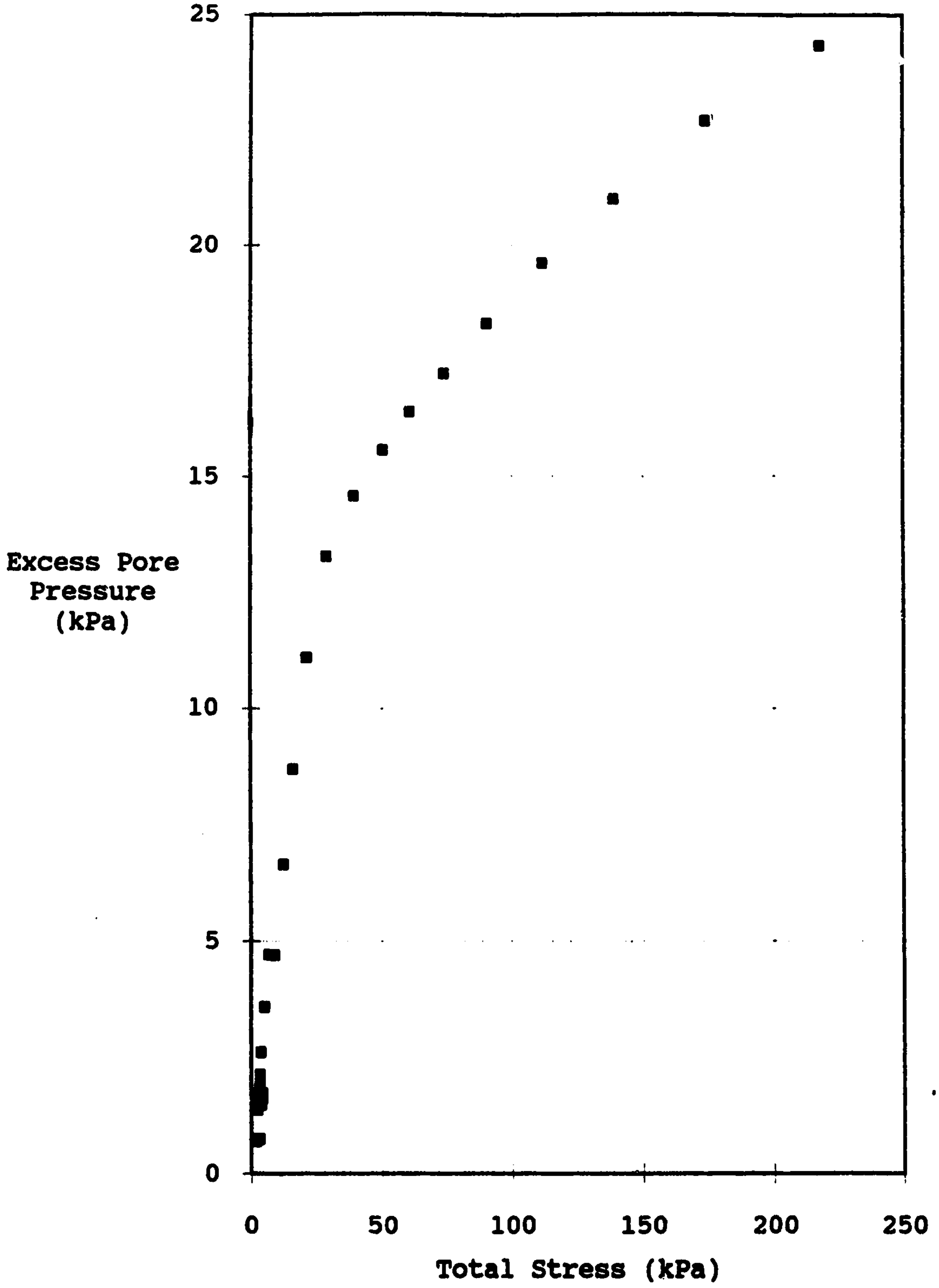


Figure C.15 Tailings Batch #2 - Constant Rate of Deformation Test #1 - Excess Pore Pressure Plot

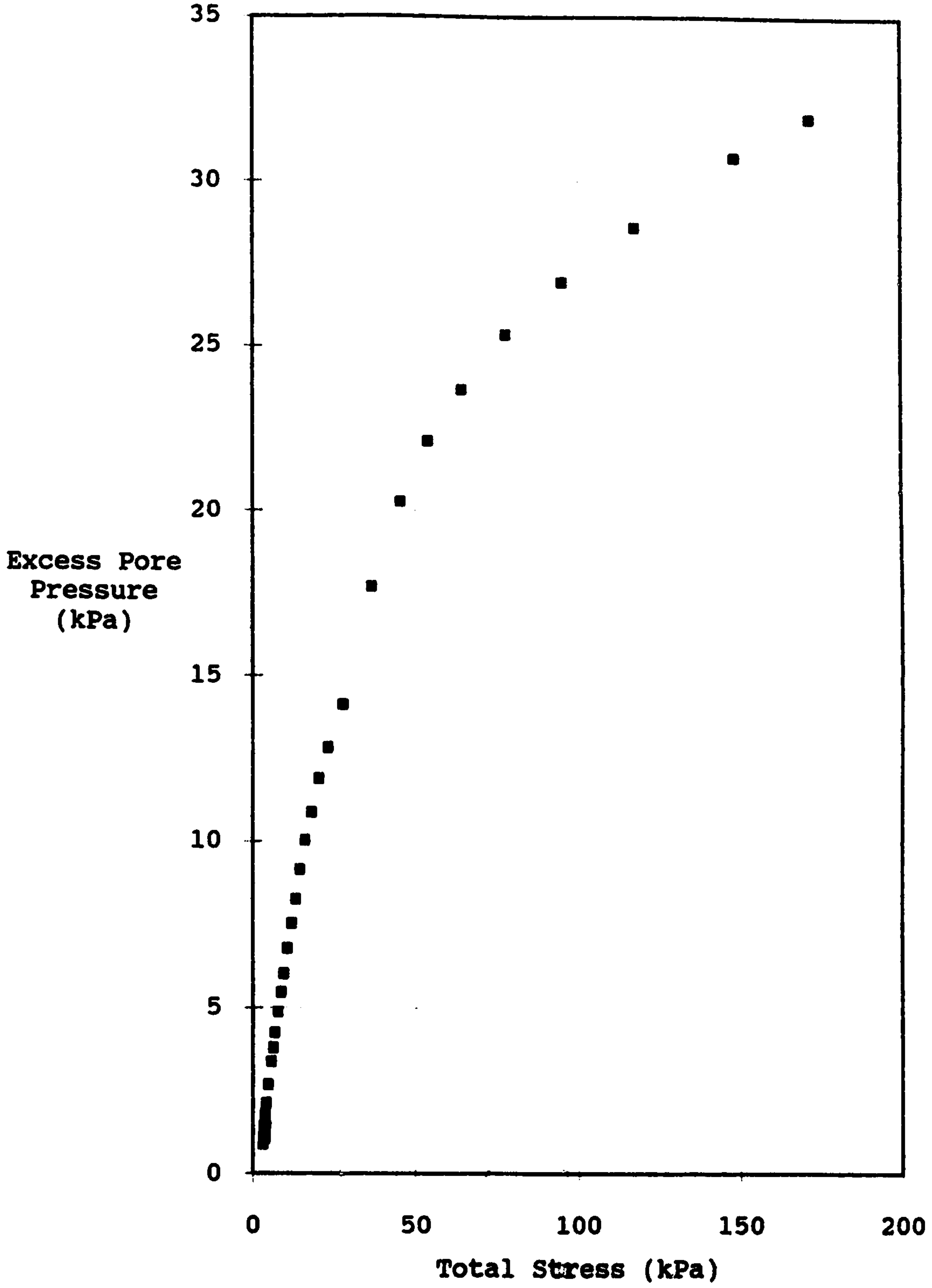


Figure C.16 Tailings Batch #2 - Constant Rate of Deformation Test #2 - Excess Pore Pressure Plot

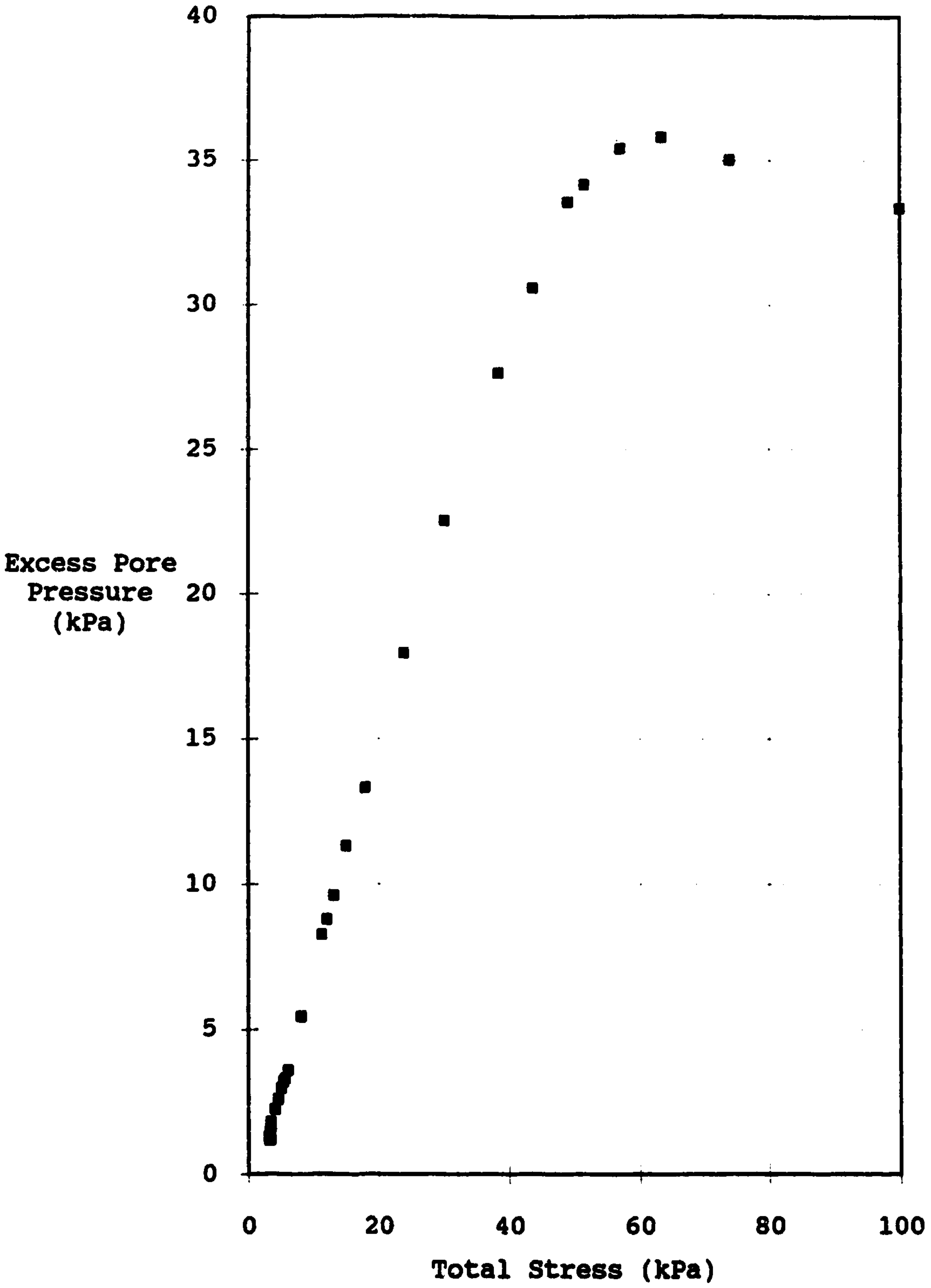


Figure C.17 Tailings Batch #2 - Constant Rate of Deformation Test #3 - Excess Pore Pressure Plot

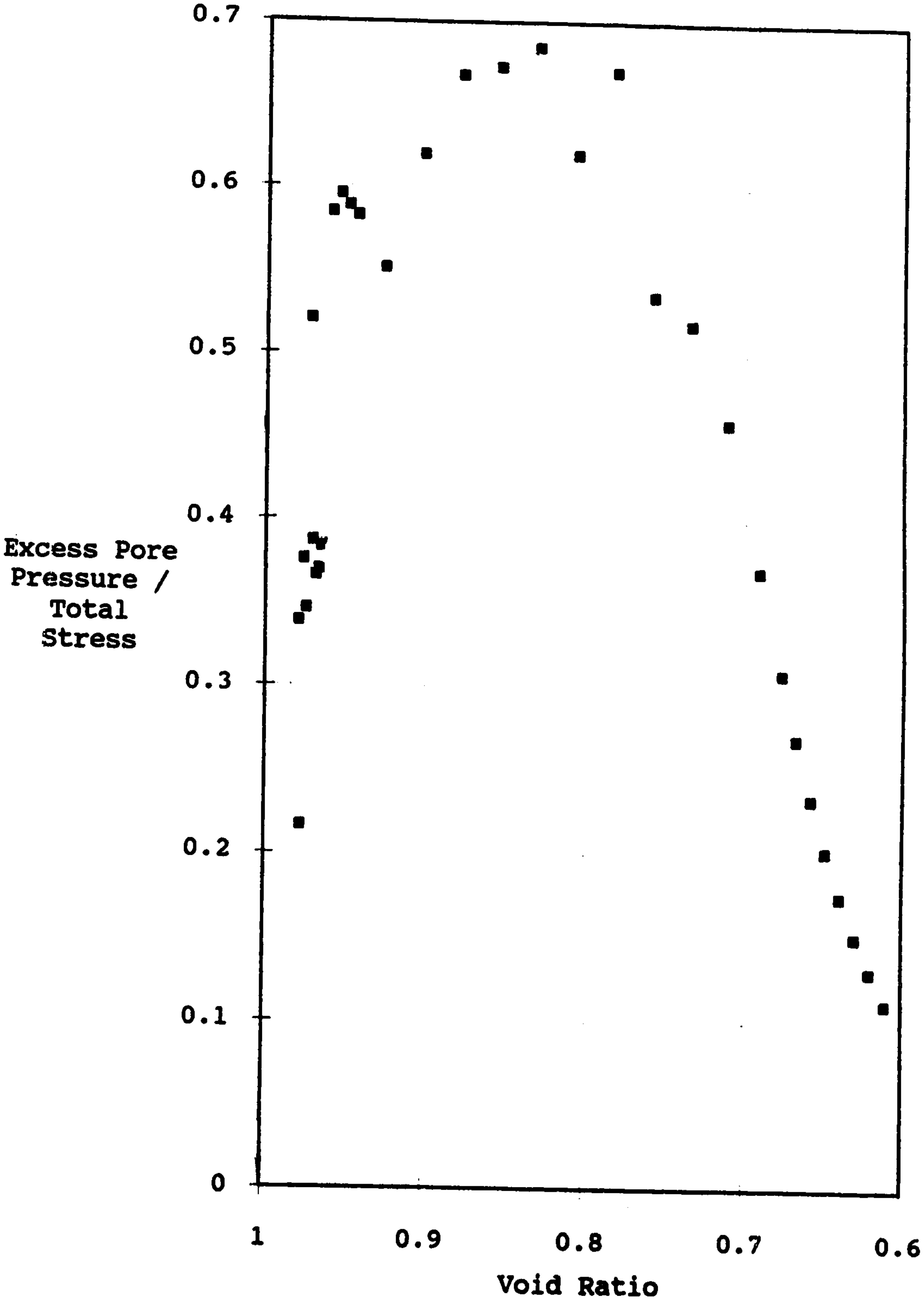


Figure C.18 Tailings Batch #2 - Constant Rate of Deformation Test #1 - Excess Pore Pressure as a fraction of Total Stress

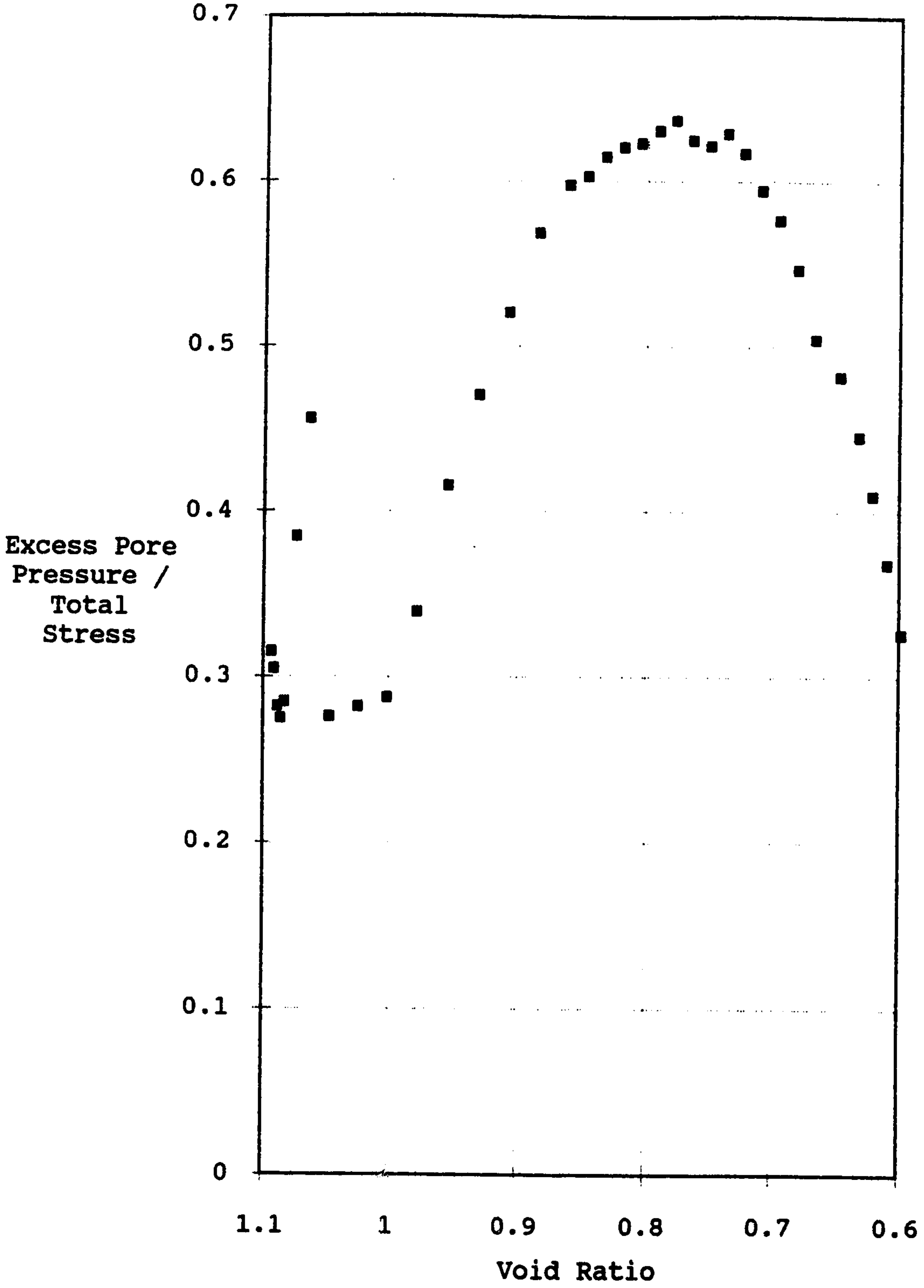


Figure C.19 Tailings Batch #2 - Constant Rate of Deformation Test #2 - Excess Pore Pressure as a fraction of Total Stress

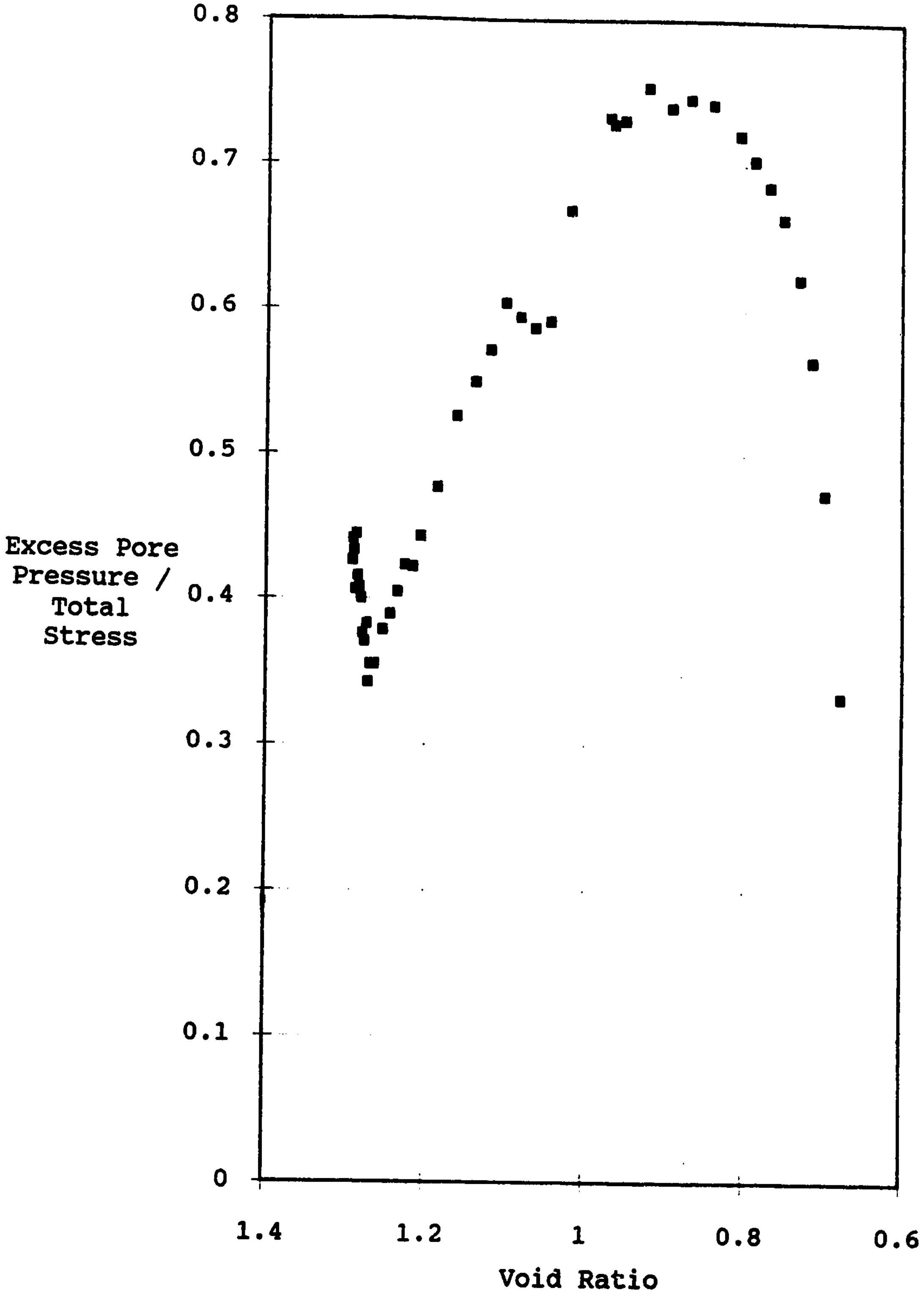


Figure C.20 Tailings Batch #2 - Constant Rate of Deformation Test #1 - Excess Pore Pressure as a fraction of Total Stress

Appendix D - Field Prediction Plots

The plots for determining the power law variables for the consolidation programs are in Figures D.1 to D.4. The laboratory data are plotted as points and the power laws as dashed lines.

The comparison plts of the predicted to actual settlement curves for the five cases where they are in close agreement are in Figures D.5 to D.8.

The plots of tailings thickness with time, void ratio profile and excess pore pressure profile for 9.16 m/yr of tailings are in Figures D.9 to D.16. The corresponding plots for 18.31 m/yr are in Figures D.17 to D.20 and for 36.62 m/yr are in Figures D.21 to D.24.

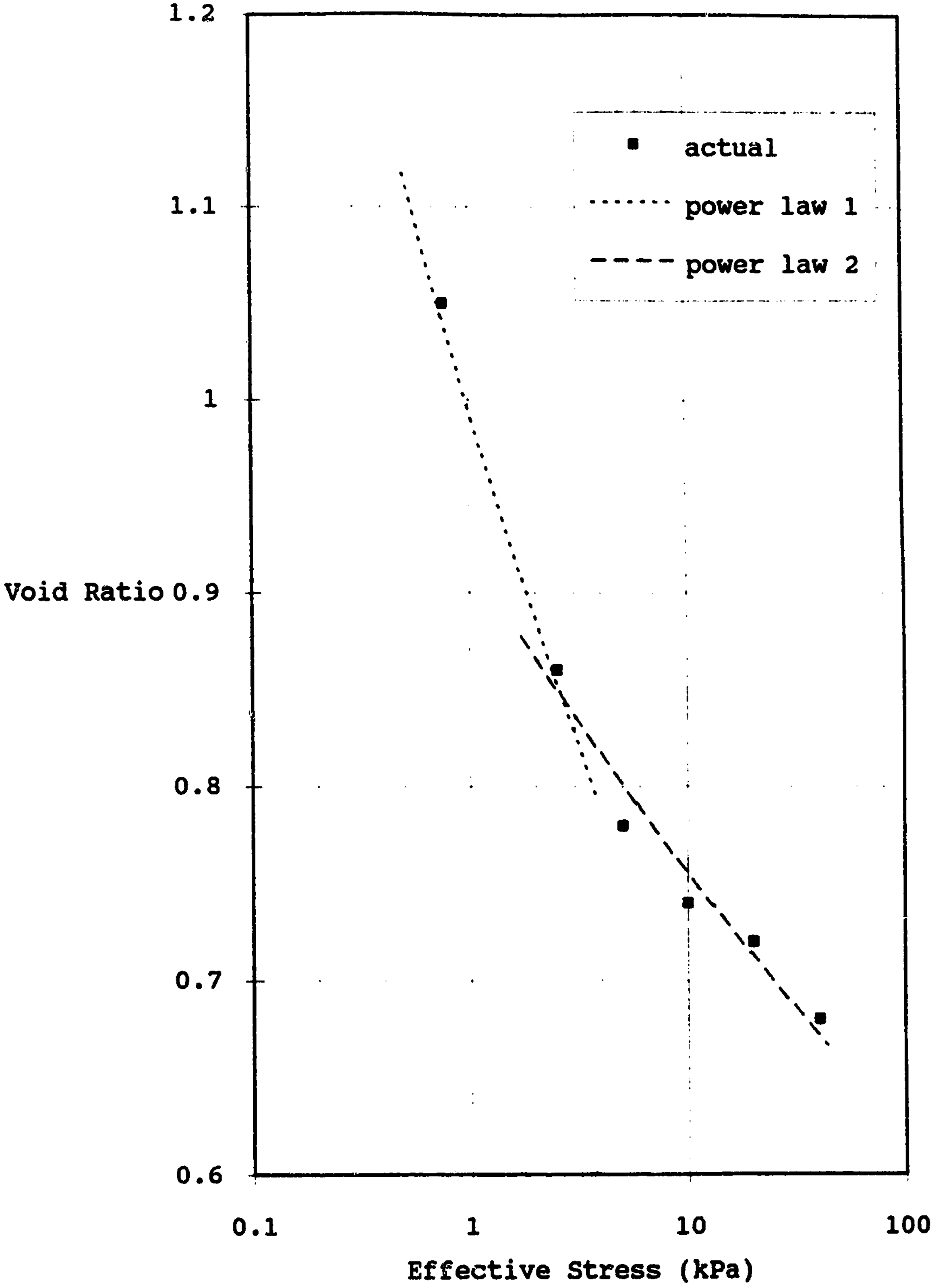


Figure D.1 Compressibility Relationship for Tailings Batch #1

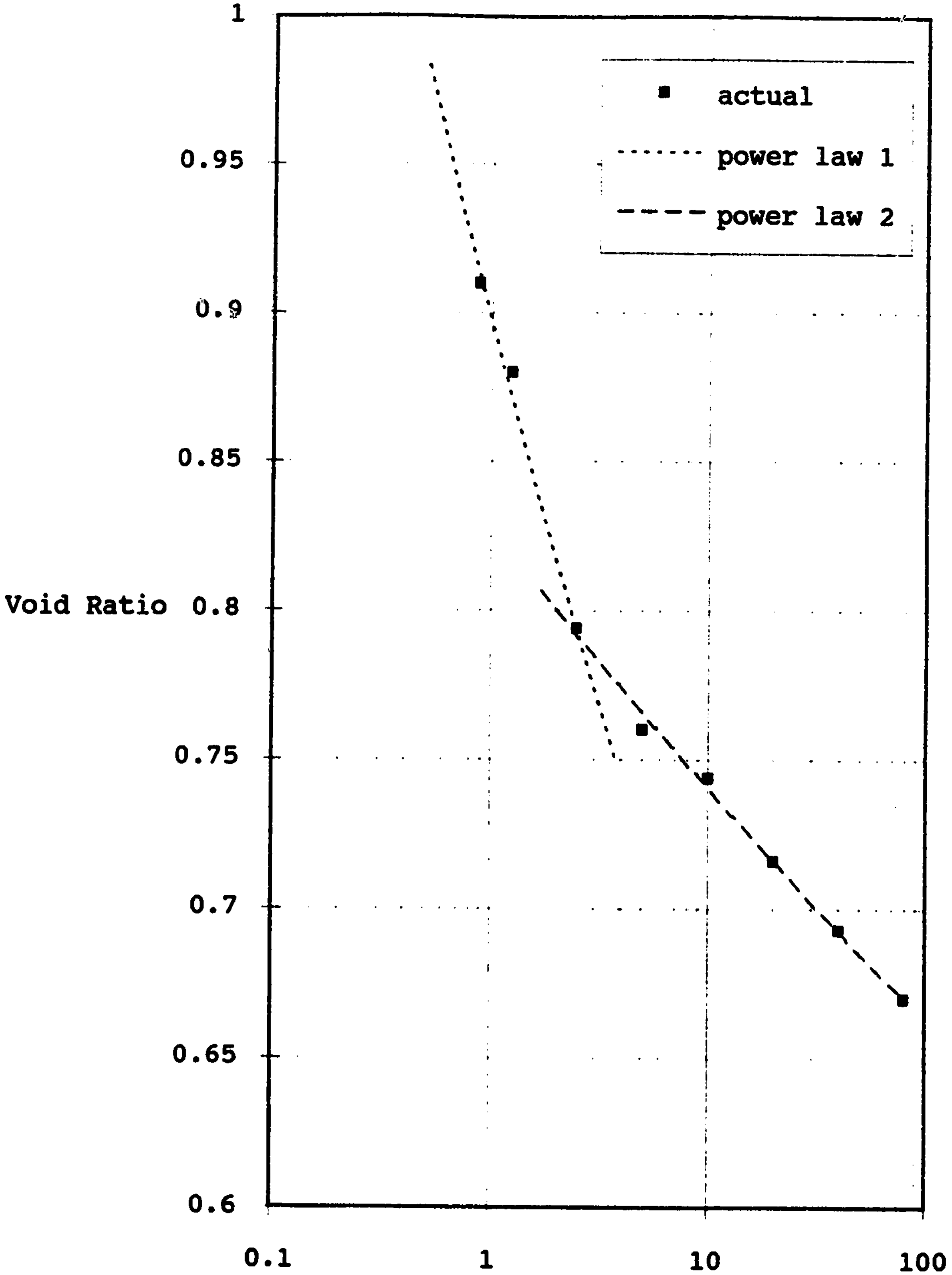


Figure D.2 Compressibility Relationship for Tailings Batch #2

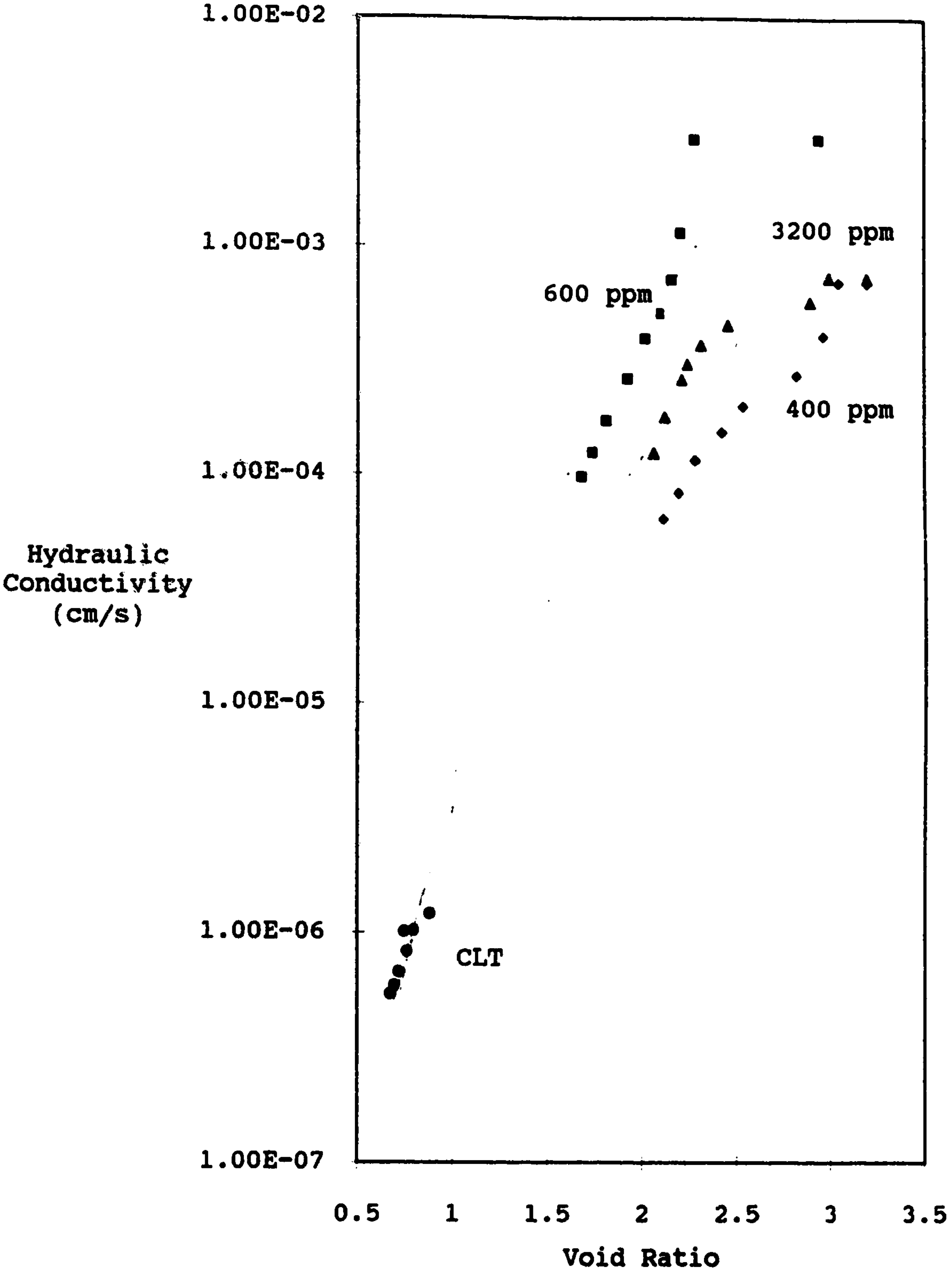


Figure D.3 Hydraulic Conductivity Analysis for Tailings Batch #1

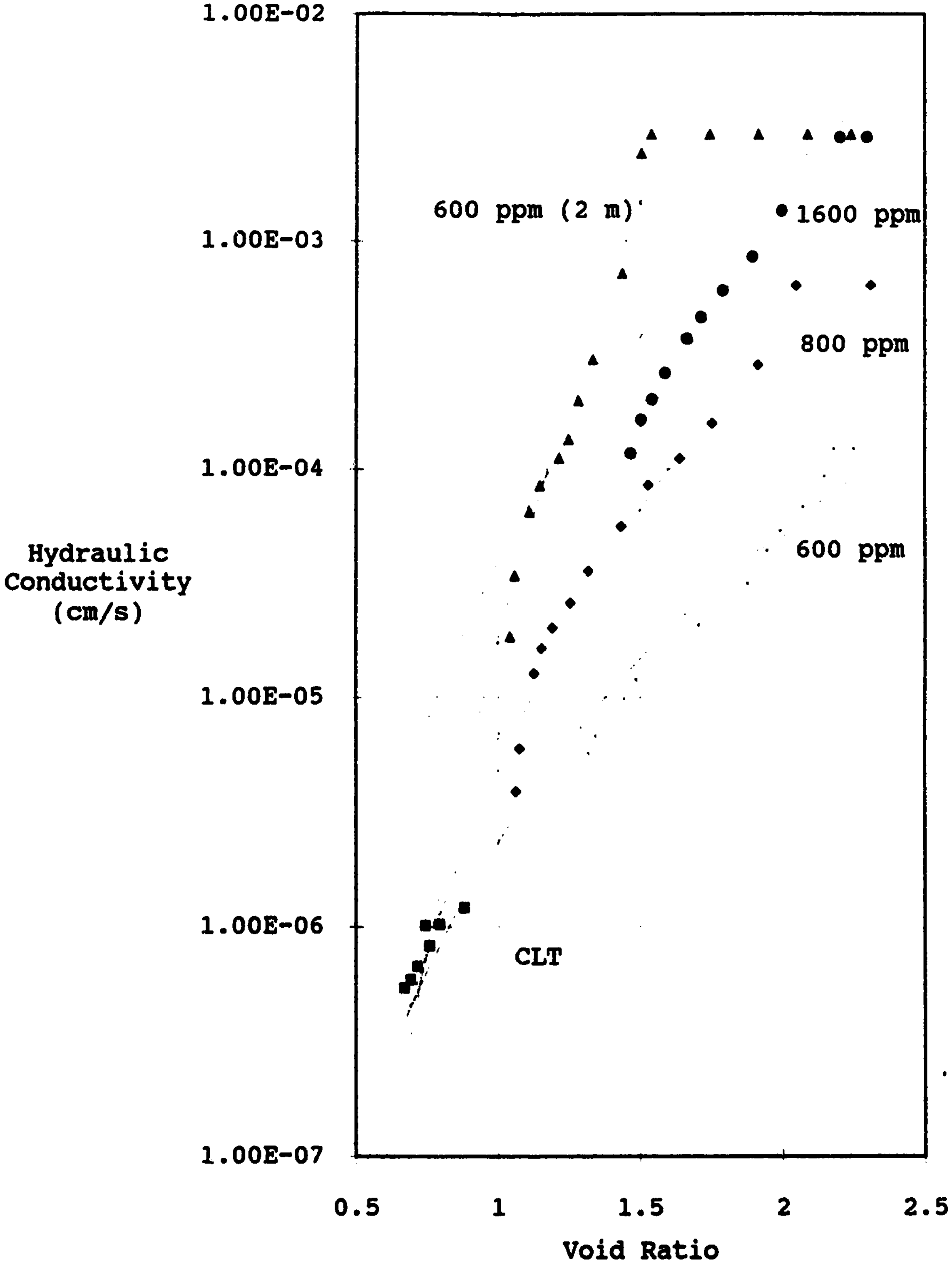


Figure D.4 Hydraulic Conductivity Analysis for Tailings Batch #2

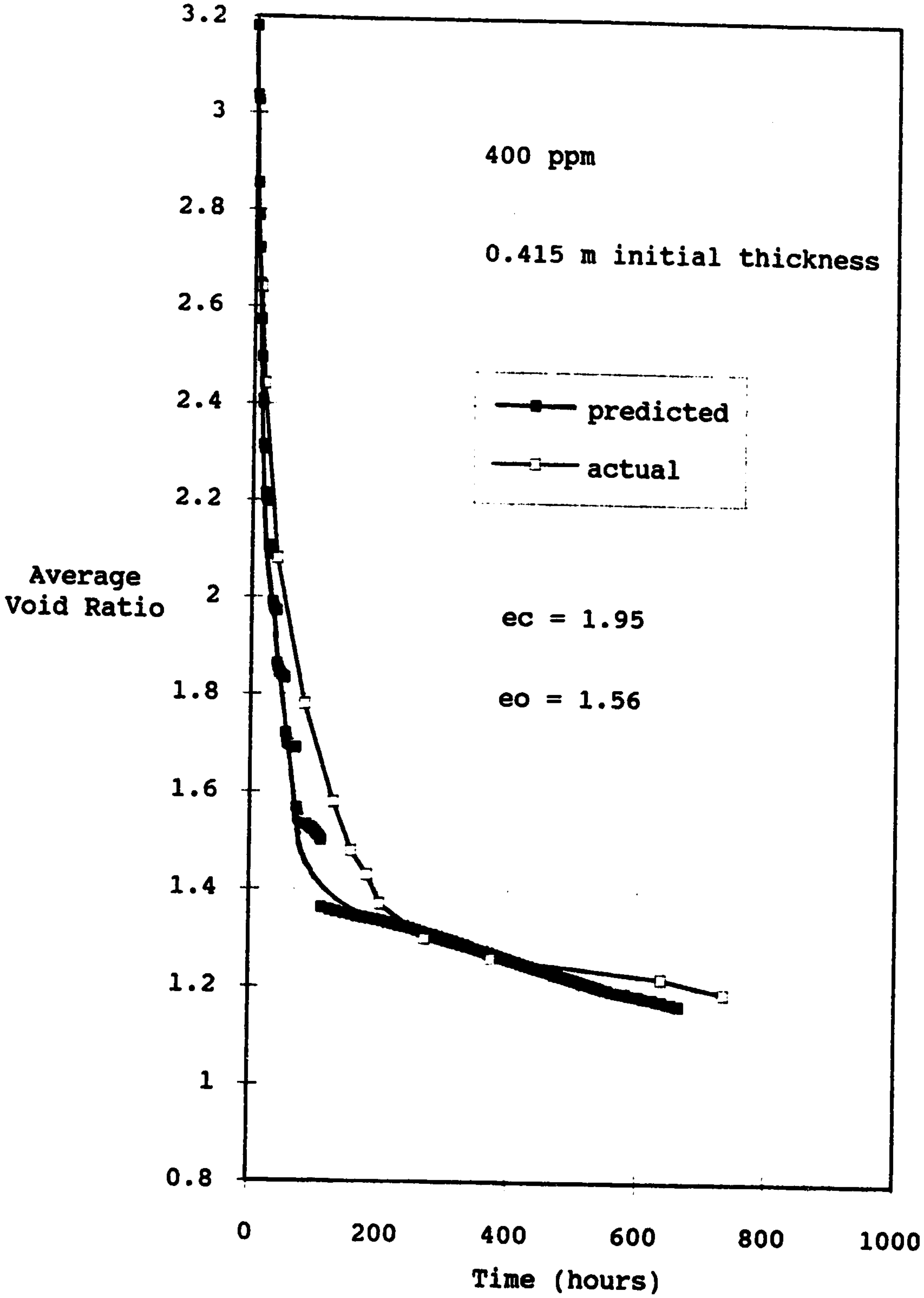


Figure D.5 Predicted vs Actual Self-Weight Sedimentation and Consolidation - Tailings Batch #1

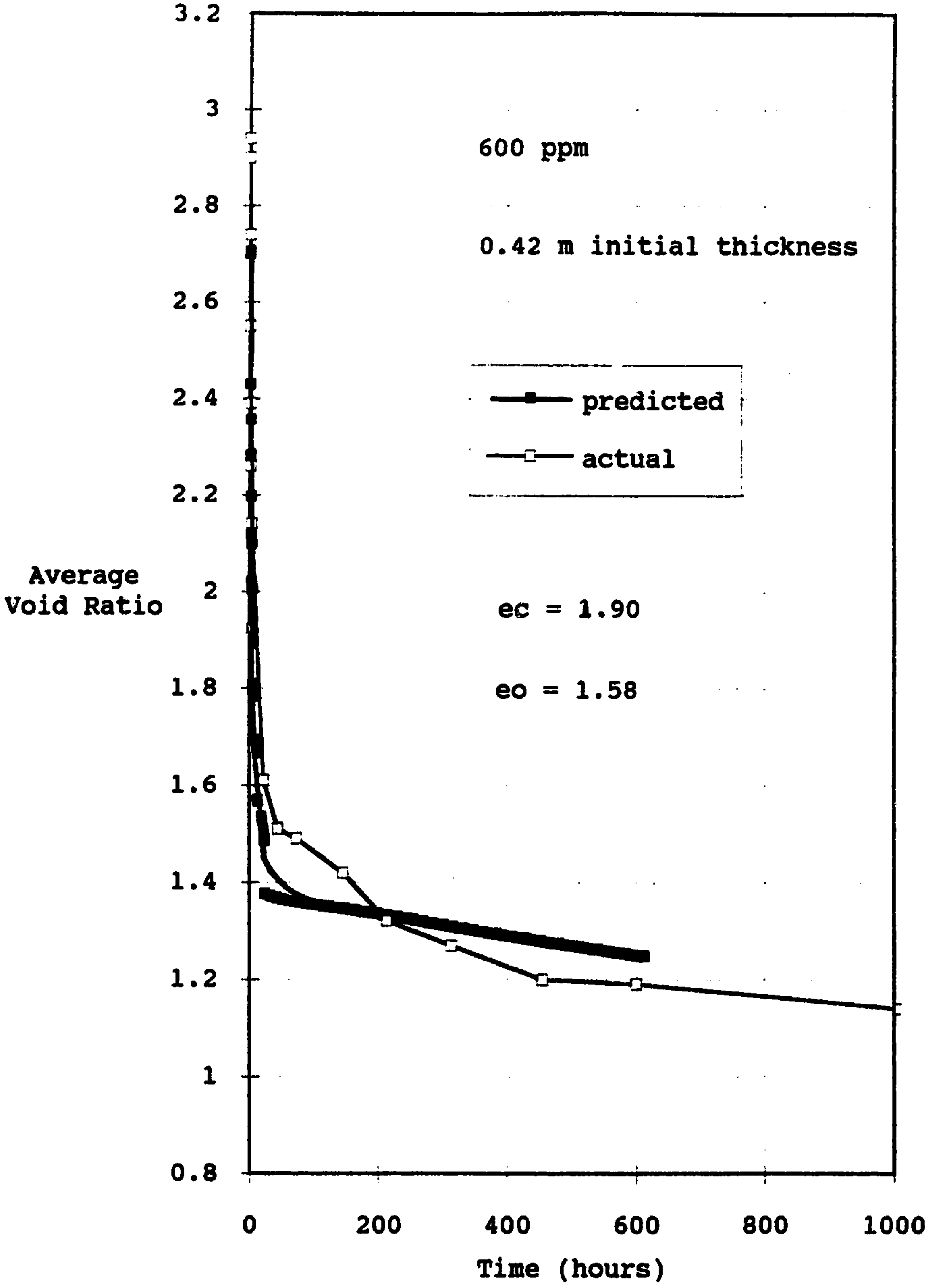


Figure D.6 Predicted vs Actual Self-Weight Sedimentation and Consolidation - Tailings Batch #1

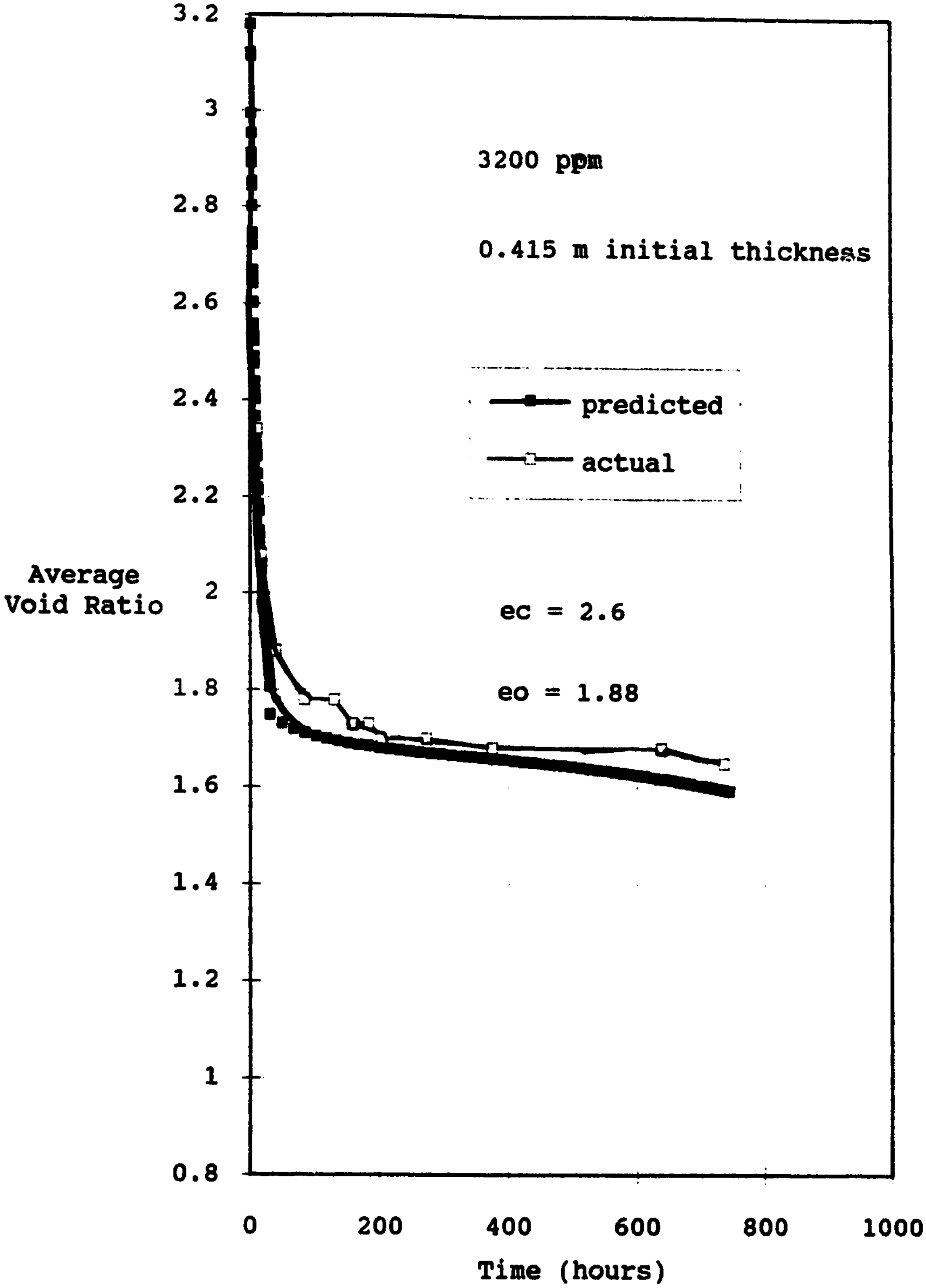


Figure D.7 Predicted vs Actual Self-Weight Sedimentation and Consolidation - Tailings Batch #1

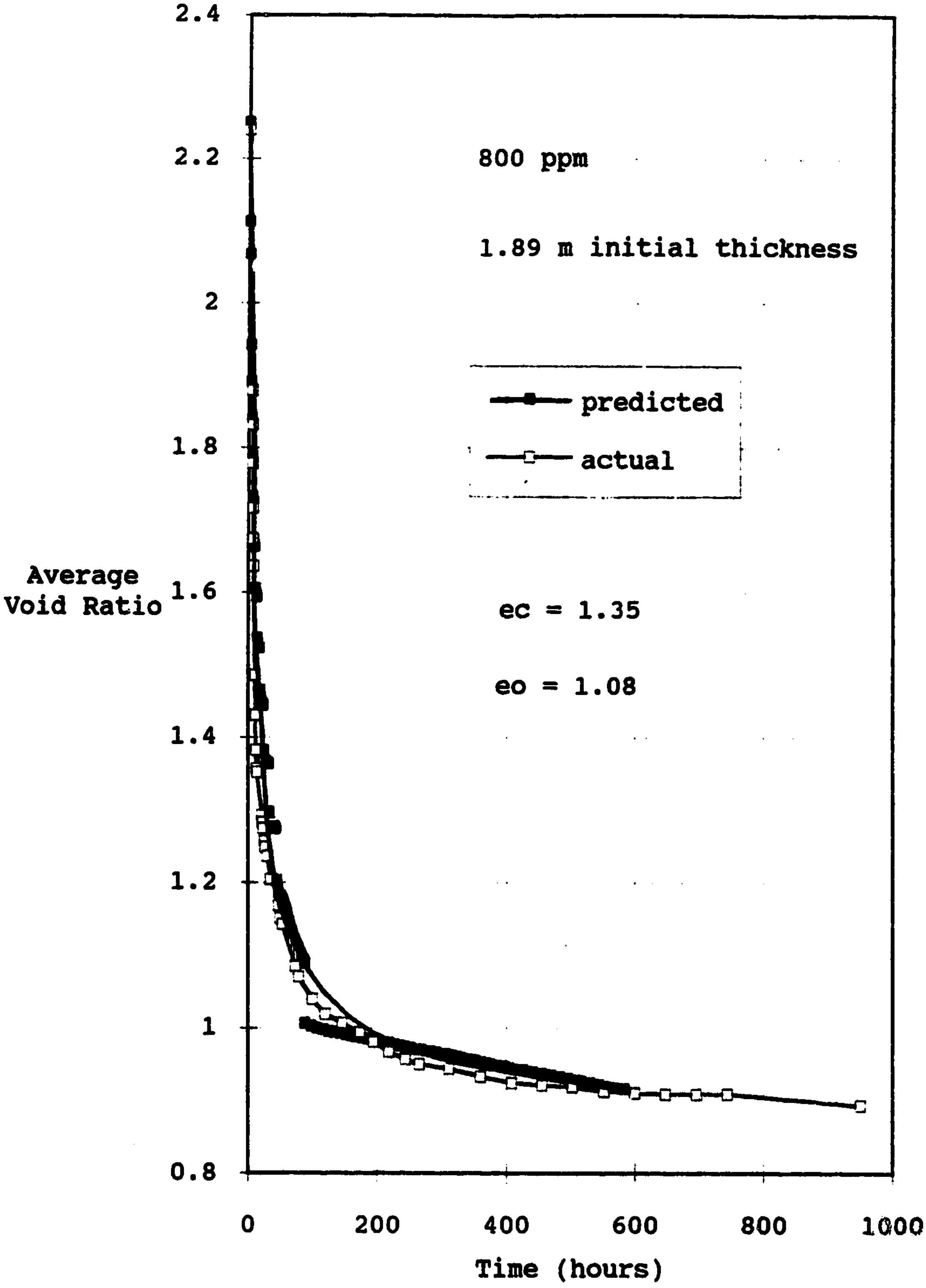


Figure D.8 Predicted vs Actual Self-Weight Sedimentation and Consolidation - Tailings Batch #2

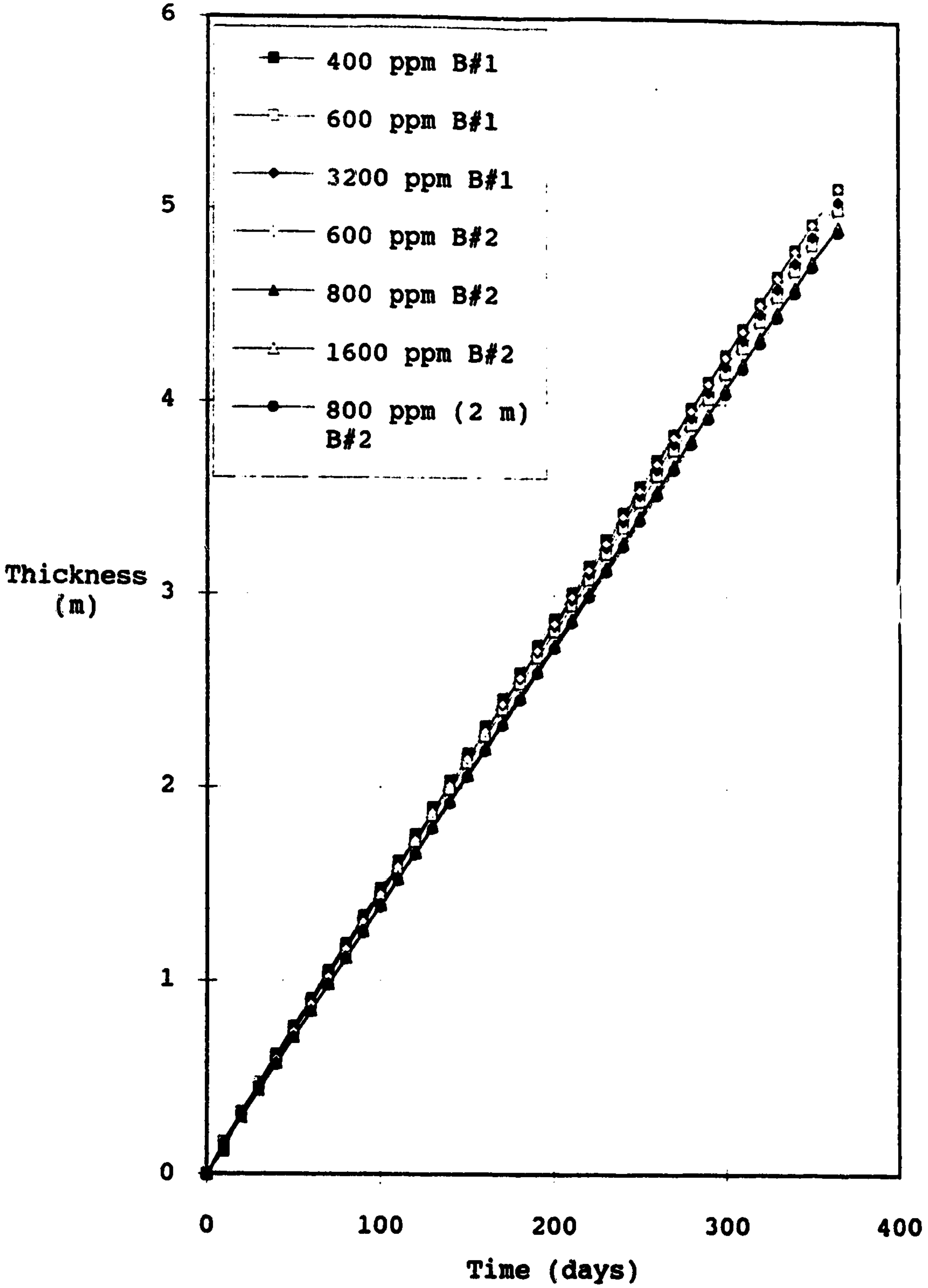


Figure D.9 Tailings Accumulation In-Pit - 9.16 m/yr

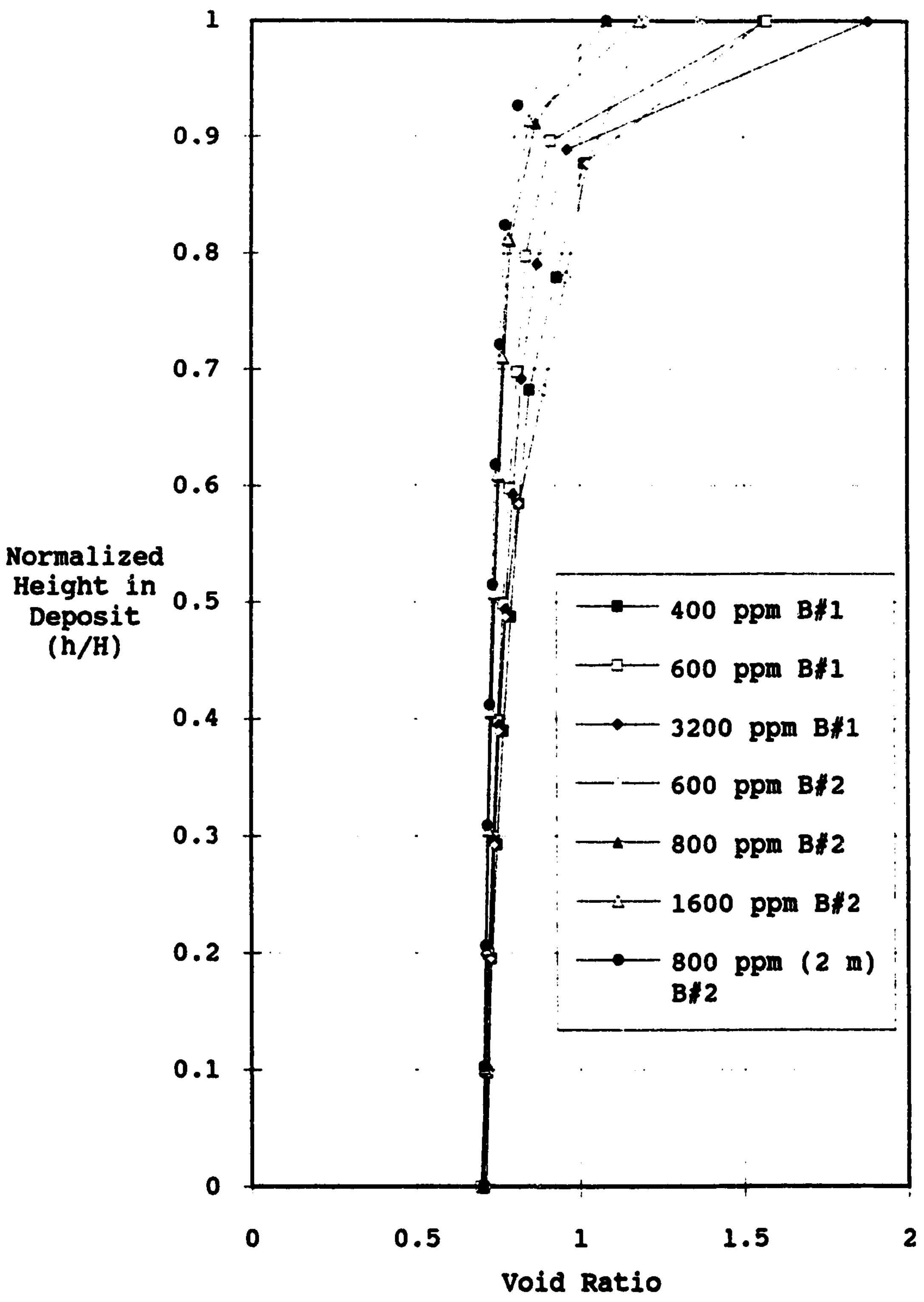


Figure D.10 Void Ratio Profile after 1 Year - 9.16 m/yr

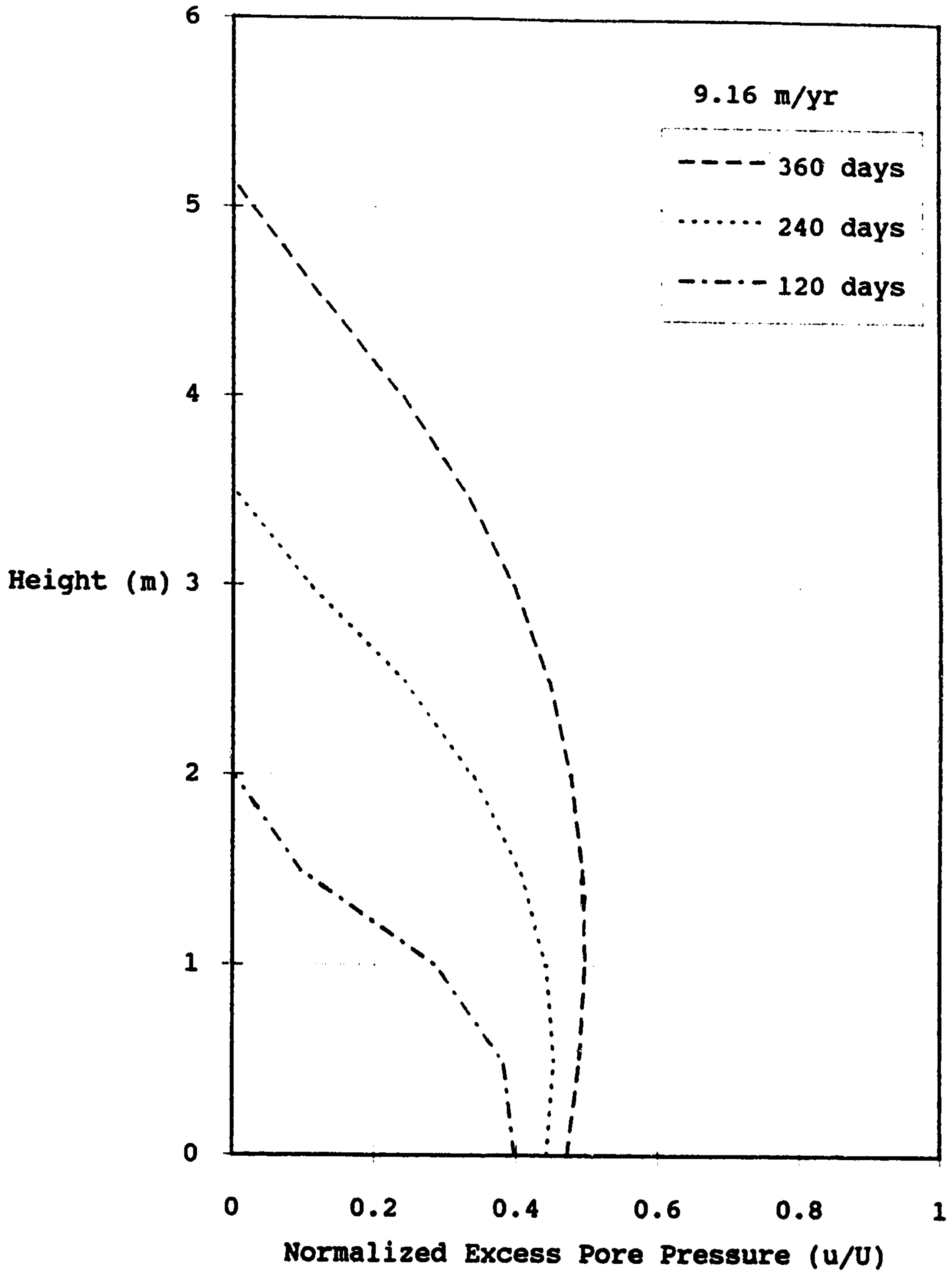


Figure D.11 Normalized Excess Pore Pressures for In-Pit Disposal - Tailings Batch #1 - 400 ppm

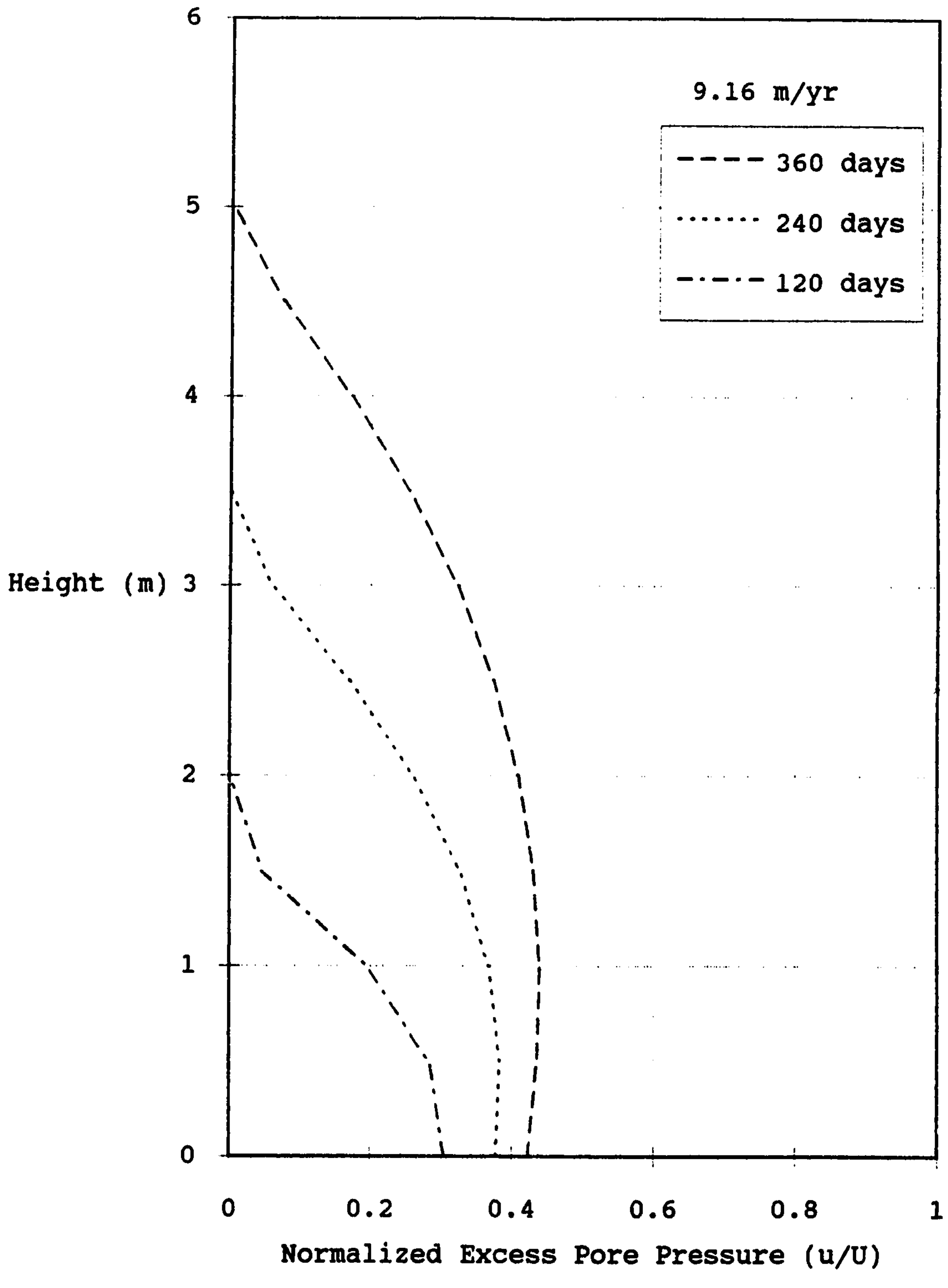


Figure D.12 Normalized Excess Pore Pressures for In-Pit Disposal - Tailings Batch #1 - 600 ppm

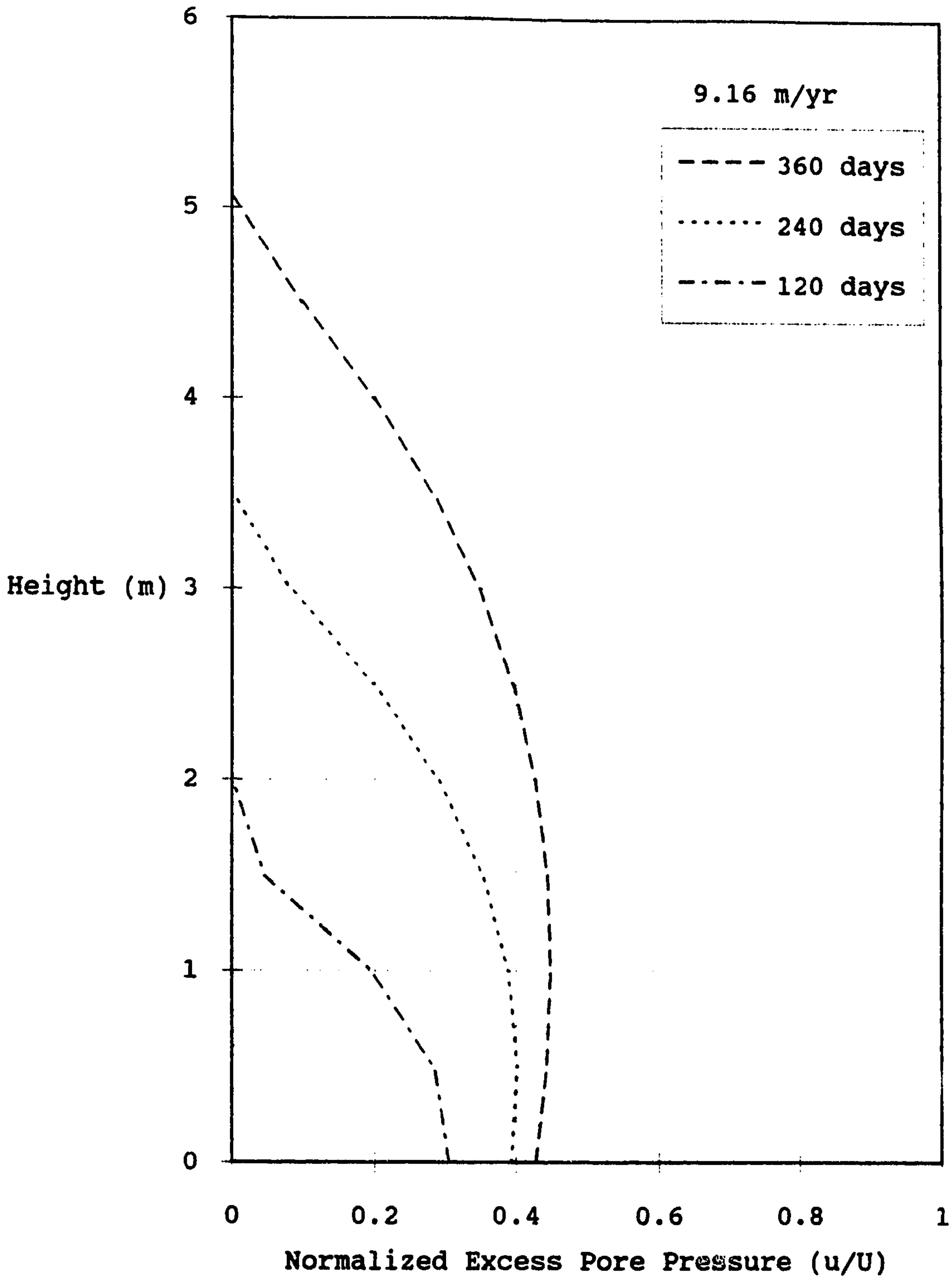


Figure D.13 Normalized Excess Pore Pressures for In-Pit Disposal - Tailings Batch #1 - 3200 ppm

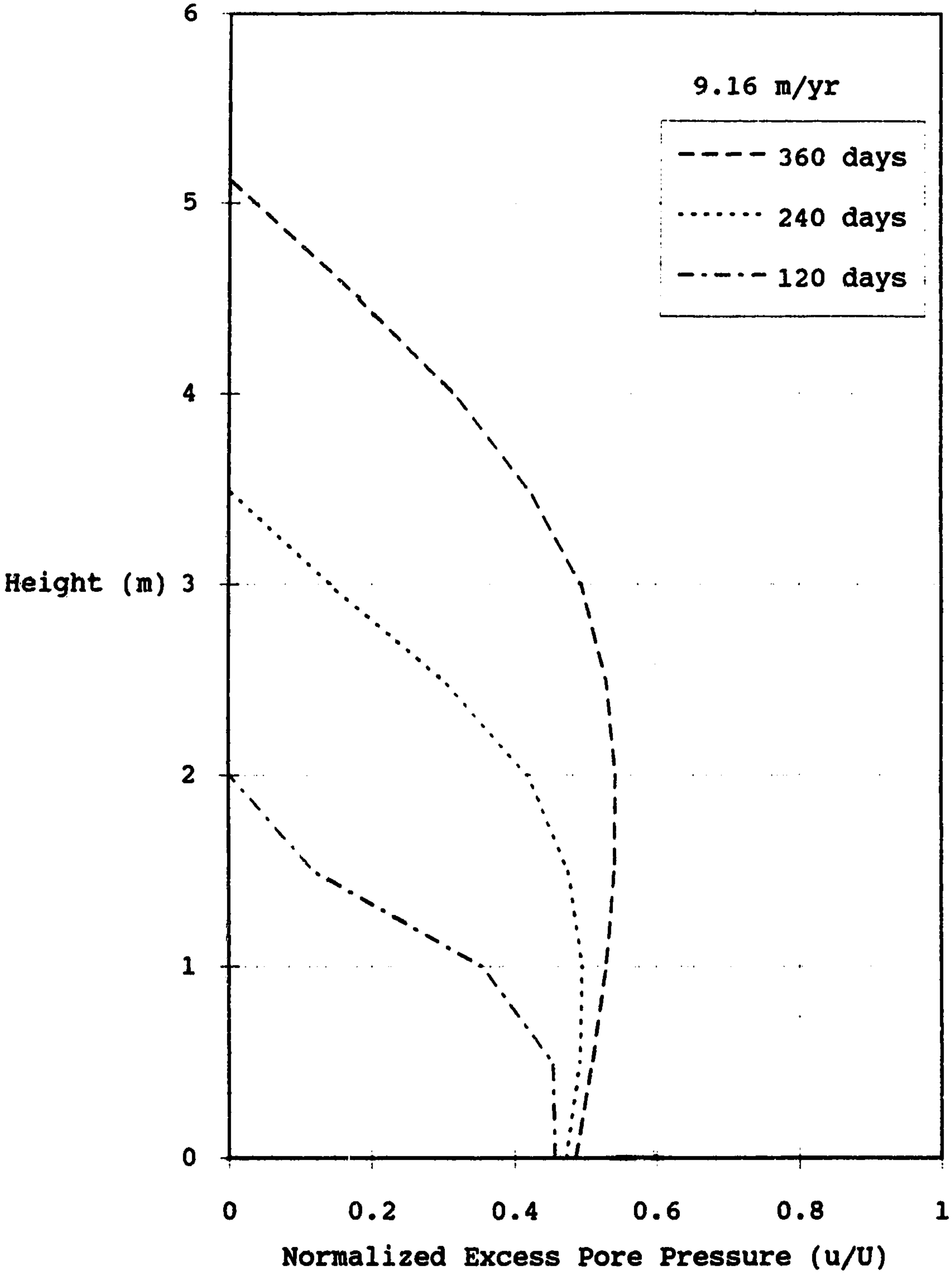


Figure D.14 Normalized Excess Pore Pressures for In-Pit Disposal - Tailings Batch #2 - 600 ppm

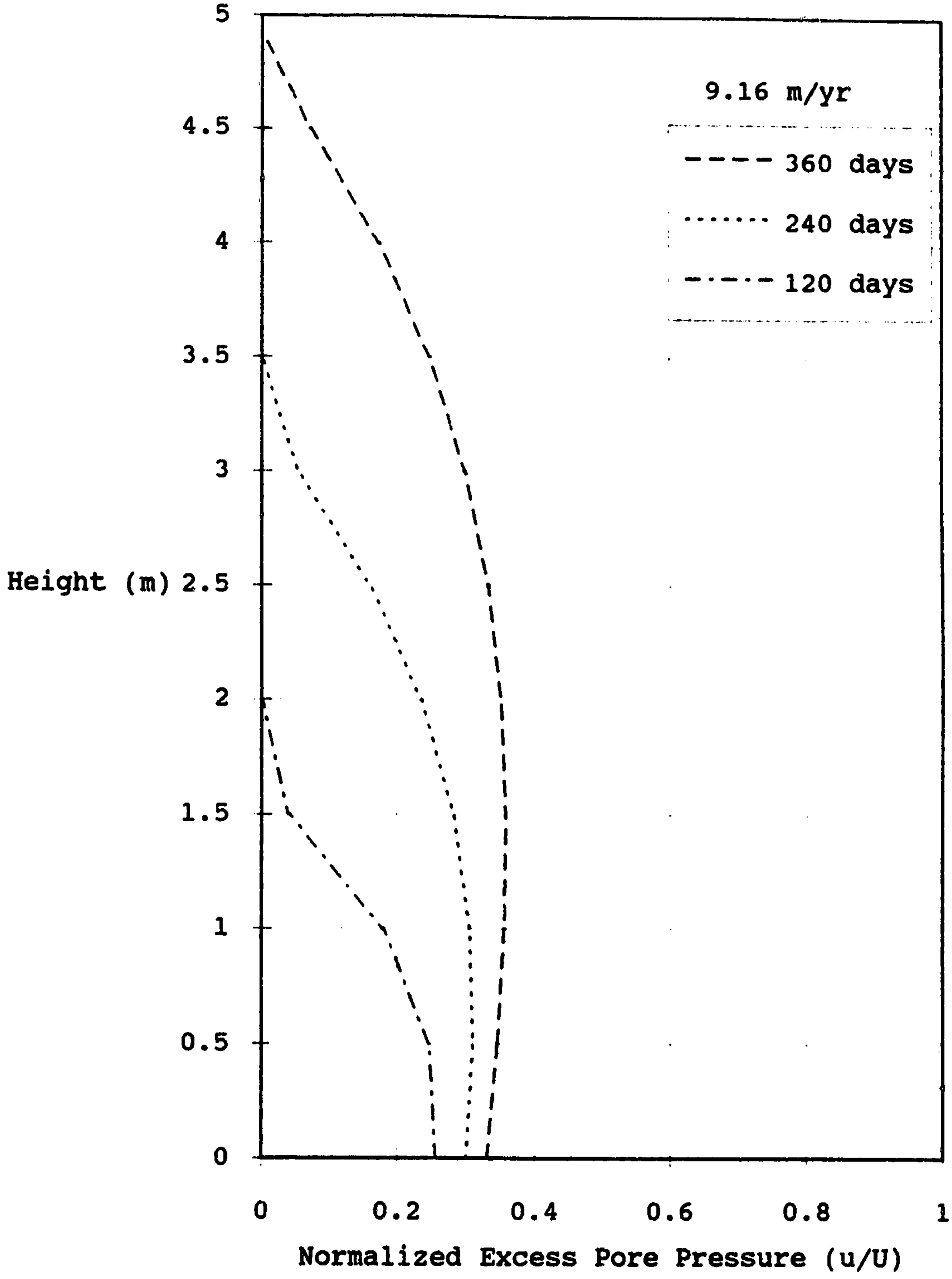


Figure D.15 Normalized Excess Pore Pressures for In-Pit Disposal - Tailings Batch #2 - 1600 ppm

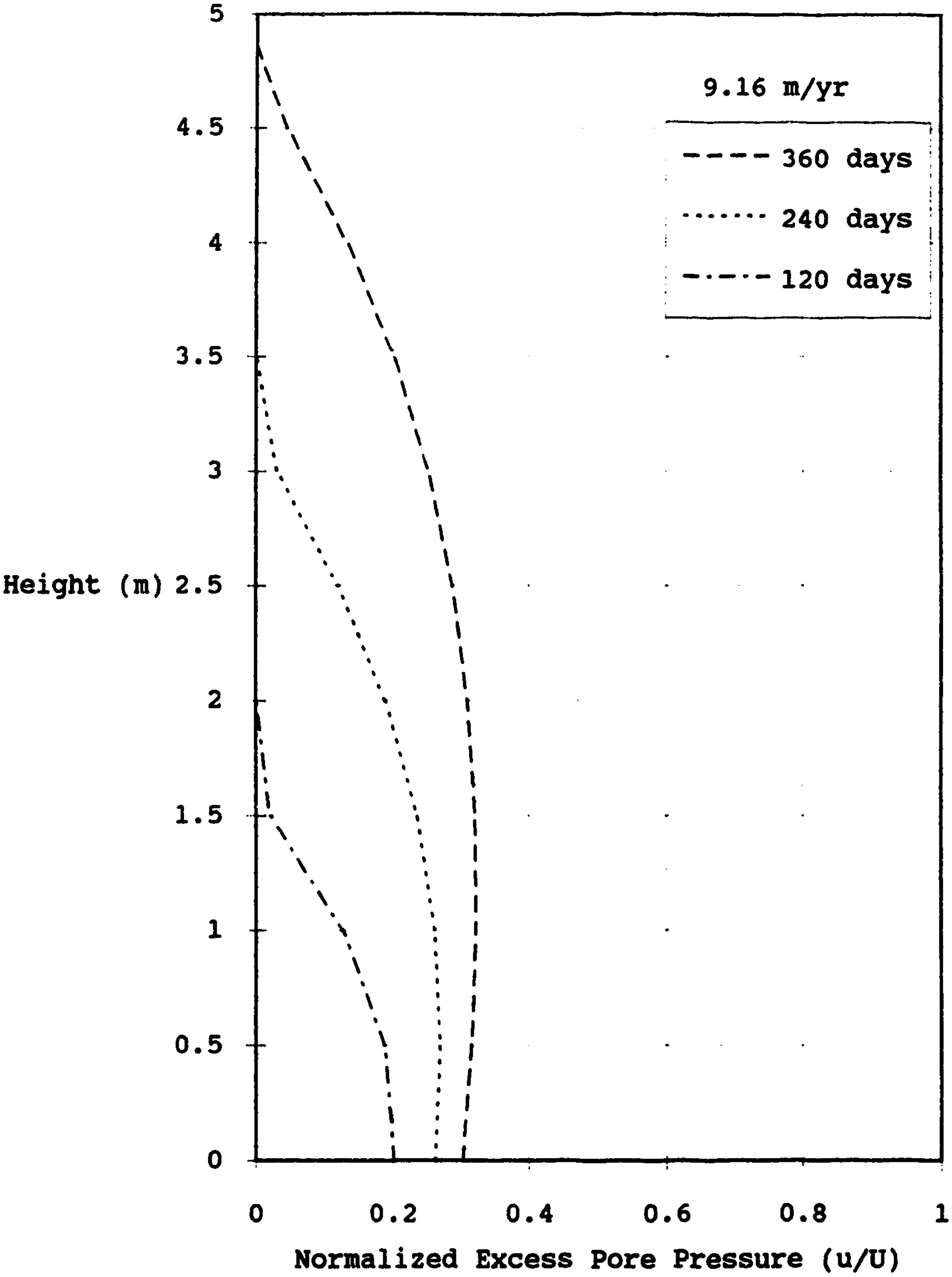


Figure D.16 Normalized Excess Pore Pressures for In-Pit Disposal - Tailings Batch #2 - 800 ppm (2 m)

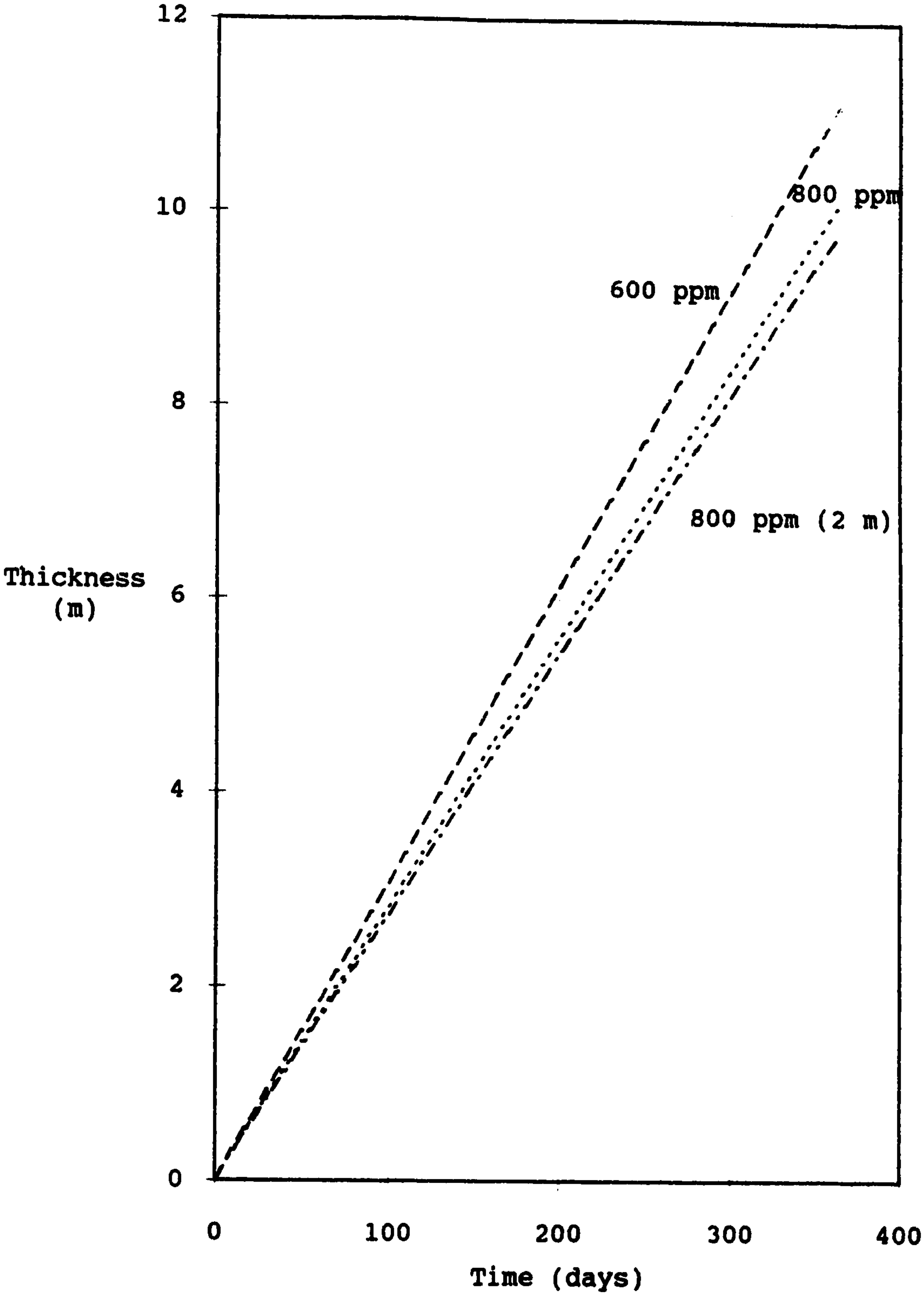


Figure D.17 Tailings Accumulation In-Pit - 18.31 m/yr

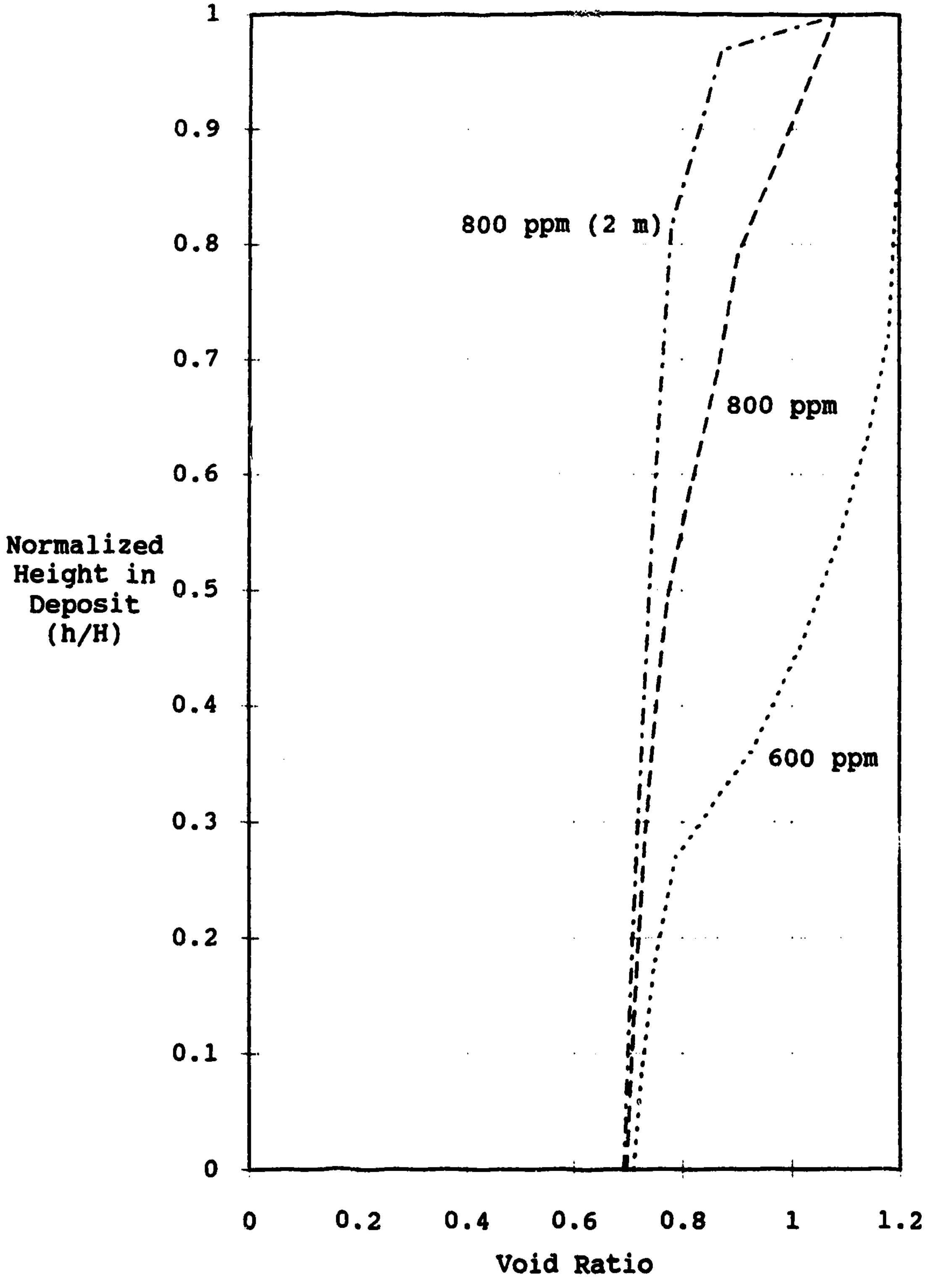


Figure D.18 Void Ratio Profile after 1 Year - 18.31 m/yr

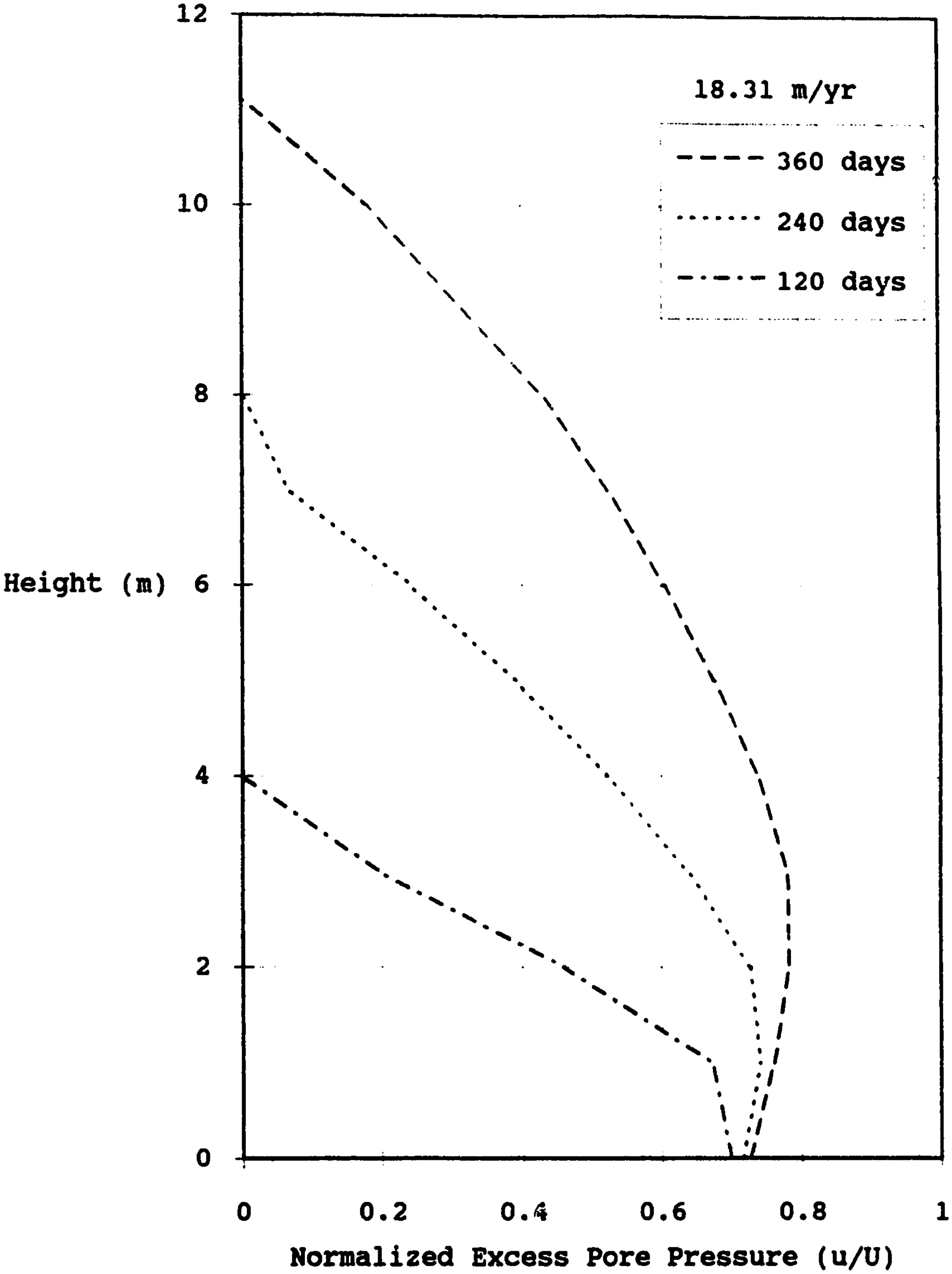


Figure D.19 Normalized Excess Pore Pressures for In-Pit Disposal - Tailings Batch #2 - 600 ppm

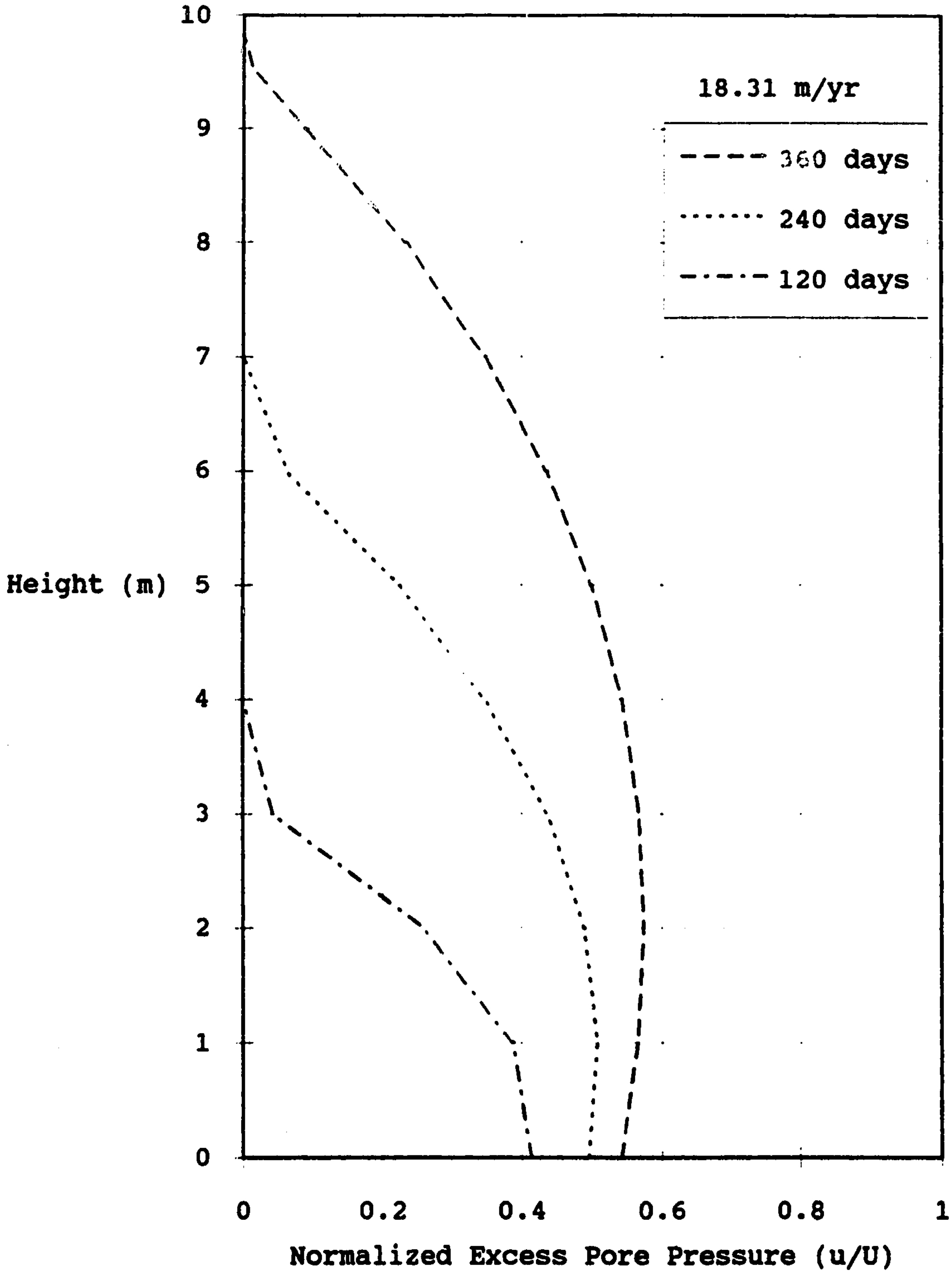


Figure D.20 Normalized Excess Pore Pressures for In-Pit Disposal - Tailings Batch #2 - 800 ppm (2 m)

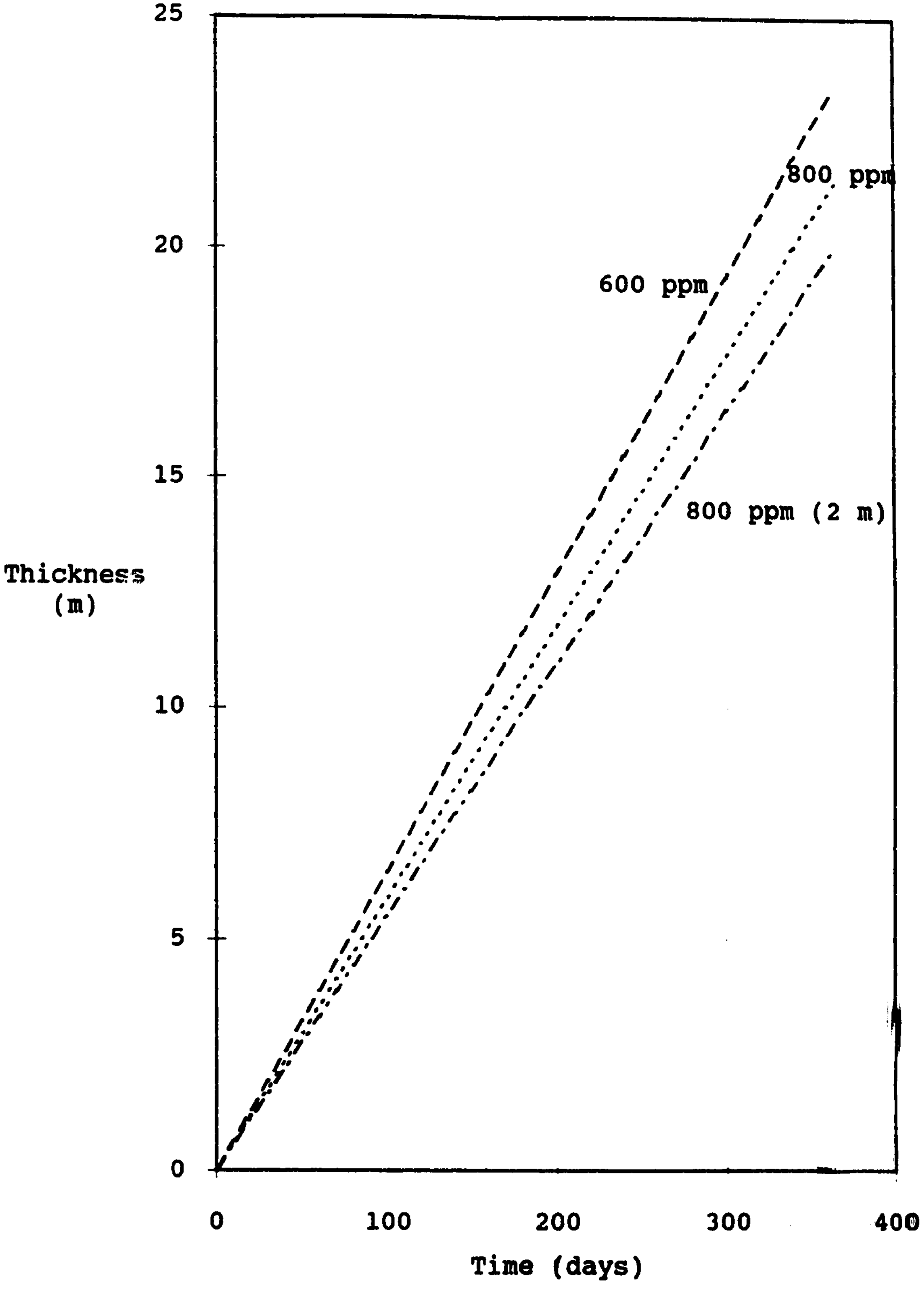


Figure D.21 Tailings Accumulation In-Pit - 36.62 m/yr

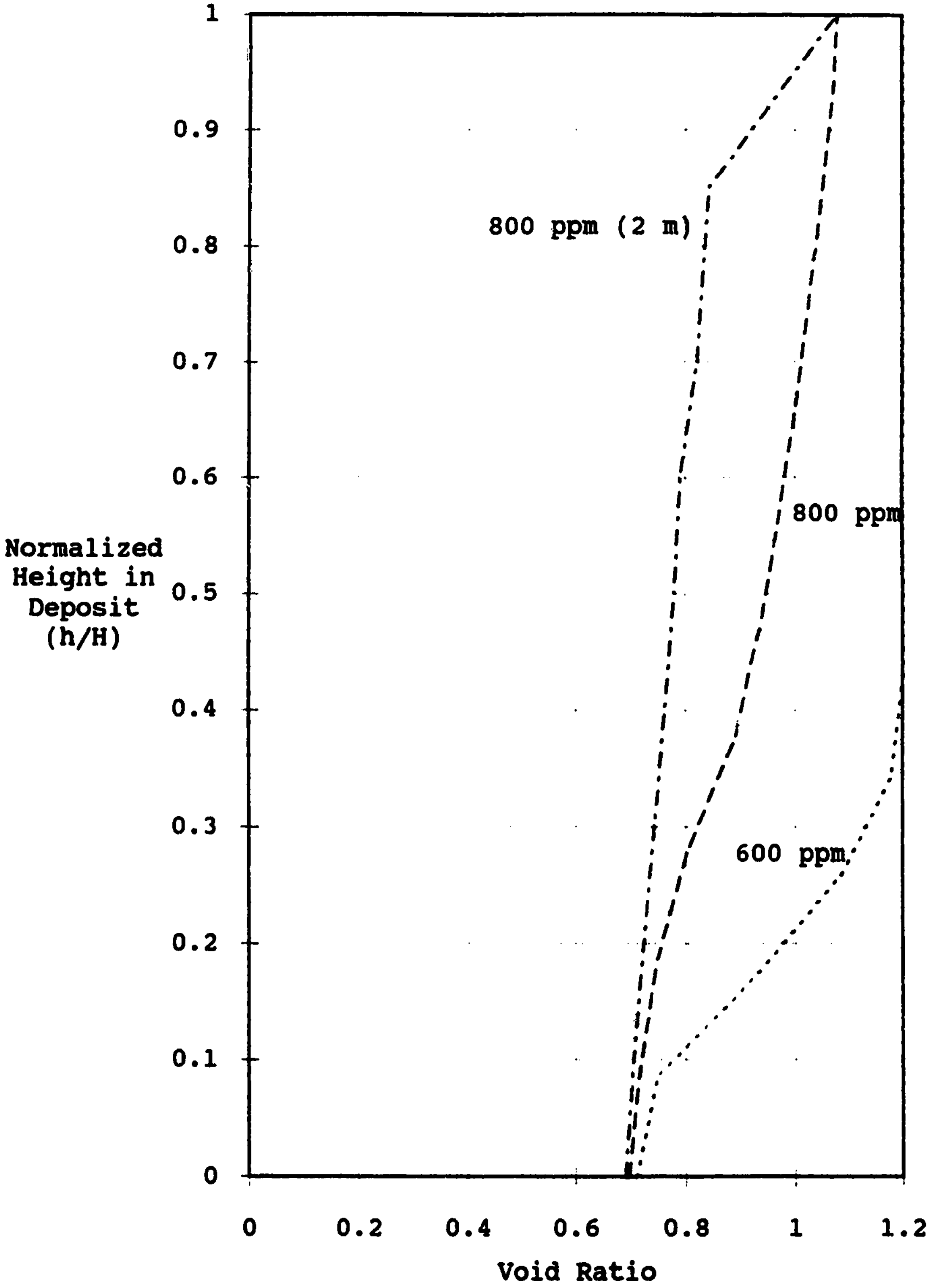


Figure D.22 Void Ratio Profile after 1 Year - 36.62 m/yr

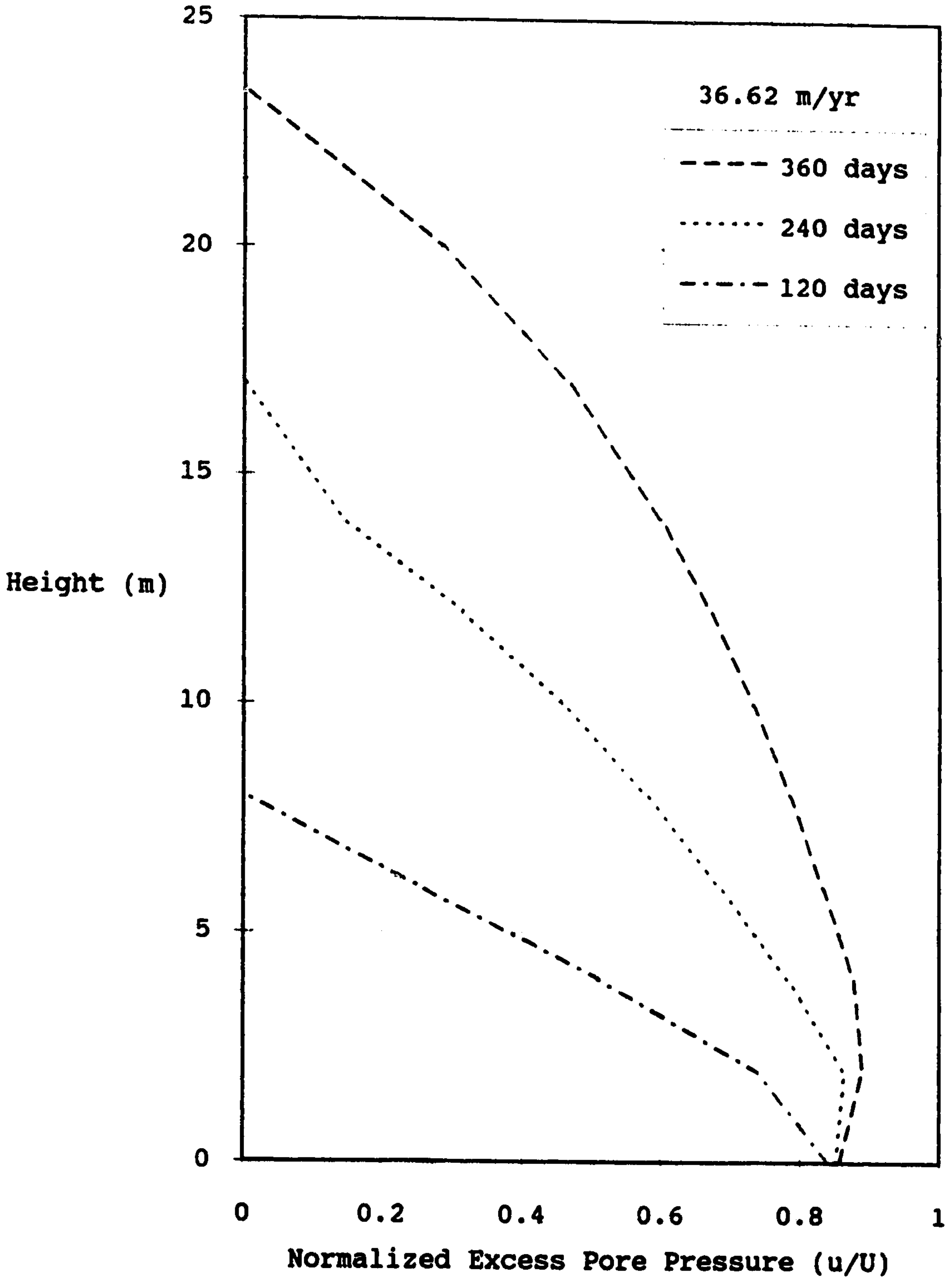


Figure D.23 Normalized Excess Pore Pressures for In-Pit Disposal - Tailings Batch #2 - 600 ppm

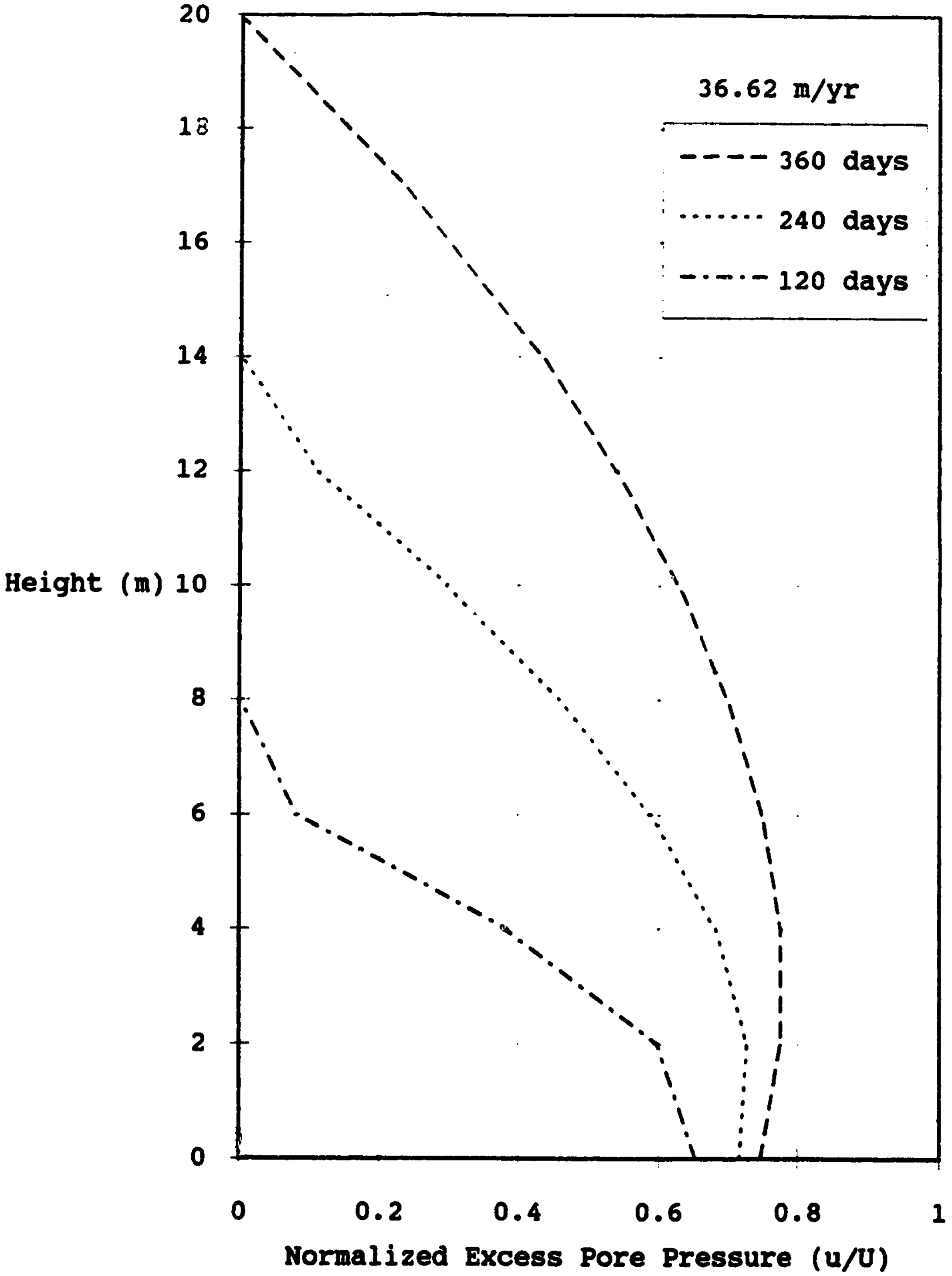


Figure D.24 Normalized Excess Pore Pressures for In-Pit Disposal - Tailings Batch #2 - 800 ppm (2 m)