THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
Department of Civil Engineering

Interim Report

ENGINEERING PROPERTIES AND DEWATERING CHARACTERISTICS OF RED MUD TAILINGS

by

Donald H. Gray
Frank Somogyi

DRDA Project 340364

supported by:

The Alcoa Foundation

Pittsburgh, Pennsylvania

administered through:
DIVISION OF RESEARCH DEVELOPMENT AND ADMINISTRATION
ANN ARBOR

May 1974

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

ABSTRACT

Red mud is a ferrosilt residual derived from the processing of alumina ores. Red muds are normally discharged as caustic slurries (12 to 15% solids) to diked impoundments. Current domestic production of red muds exceeds 5 million tons per year from some eight alumina processing plants in the USA.

Dewatering of red mud deposits and reclamation of disposal sites pose some difficult problems. This report reviews present mud management and disposal practices in addition to techniques which have been employed to dewater the muds. Known geotechnical properties of red muds and similar tailings are likewise reviewed. Consolidation models and theories which might be used to predict the compression and dewatering behavior of red muds are also examined.

Laboratory tests are being run on samples from two of Alcoa's plants, viz., Point Comfort and Mobile. A parametric variation type of study on reconstituted samples of red mud from the last stage thickeners was employed rather than testing in-situ samples from the mud lakes. Significant parameters which are varied in the testing program include mud/sand ratio, dissolved solids, water content, pH, and time. The laboratory testing program is restricted to relevant geotechnical properties and analysis of the muds, viz., index properties (e.g., plasticity and gradation), composition, consolidation behavior, shear strength, compaction characteristics, leaching tests, and chemico-osmotic behavior.

Preliminary results, mainly from tests on the Mobile mud, are presented in this interim report. The significance of the results are discussed. Perhaps the most important finding to date is the sensitivity of engineering properties (e.g., compressibility and shear strength) to dissolved solids content in the muds.

An analysis of alternative dewatering schemes is also presented in the light of consolidation test results and dewatering methods which have been proposed or employed previously. These dewatering schemes basically involve one— or a combination of the following processes: decantation and evaporation, seepage or drainage to sand

blankets or finger drains, and consolidation under surcharge loading (either with or without vertical drains).

A combination dewatering approach appears the most promising. Consolidation under surcharge loading is probably a necessary final step for successful dewatering and reclamation of impounded red mud deposits. On the other hand, surcharge consolidation must be preceded by other dewatering methods, viz., self drainage, evaporation, and/or decantation, to reach a solids content sufficiently high enough to support the surcharge. The possibility of using the mud slurry itself as a surcharge by isolating it from underlying mud by means of a thin, rubber membrane is explored. It is clear from these analyses that any practical and economical dewatering scheme will require careful mud management and design of the tailings structure and impoundment.

I. INTRODUCTION

A. NATURE AND MAGNITUDE OF THE PROBLEM

Depending upon the quality of the bauxite being processed approximately 2/3 to one pound of tailings must be disposed of for each pound of alumina produced. These tailings are basically a fine grained ferrosilt which have been dubbed "red muds." Red mud production from alumina processing plants in the USA presently exceeds 5 million tons per year. Although this production of residuals is not large compared to other mineral wastes, their disposal nevertheless poses some difficult problems. The amounts and distribution of mineral waste production for all mineral processing industries are shown in Table 1.

Red muds are generated at some eight major alumina processing plants in Texas and the Southeast as shown in Table 2. The red muds investigated in the present study come from two plants operated by Alcoa, viz., Mobile, Alabama, and Point Comfort, Texas. Both these plants process bauxite coming principally from Jamaica and Surinam.

Red mud disposal practices usually consist of slurrying the mud at the processing plant to a 12 to 15 per cent solids content. The sand fraction in the tailings is normally added to the mud slurry as well. Typical mud/sand ratios may range from 1 to 7 on a dry weight basis. This mud-sand slurry is then pumped to diked impoundments. These impoundments or mud lakes as they are called in the industry, may extend over several hundred acres and have dikes with crests as high as 100 feet. The muds are usually discharged into the lakes at points along their periphery. The sand size fraction settles out fairly rapidly to form deltas around the discharge points. The fines (or slimes) are carried further out into the lake. These fines settle out slowly, and even after several years the solids content may still be under 50 per cent where the phreatic surface has not dropped below the top of the settled solids.

TABLE 1. RESIDUALS BY TYPE GENERATED BY THE MINERALS AND FOSSIL FUELS INDUSTRIES IN 1965.
(1,000 short tons)

from Vogely (1968)

Industry	Mine Waste	Mill Tailings	Washing Plant Rejects	Slag	Processing Plant Wastes	Total
Copper	286,600	174,900	----	5,200	----	466,700
Iron and Steel	117,599	100,589	----	14,689	1,000	233,877
Phosphate Rock	72	----	54,823	4,030	9,383	68,308
Lead-Zinc	2,500	17,811	----	----	----	20,311
Alumina	----	----	----	----	5,350	5,350
Bituminous Coal	12,800	----	86,800	----	----	99,600
Anthracite Coal	1/	----	2,000	----	----	2,000
Coal Ash	----	----	----	----	24,500	24,500
other	NA 3/	NA	NA	NA	NA	230,000 2/
TOTAL	419,571	293,300	143,623	23,919	40,233	1,150,646

1/ Total not available but quantities negligible and are included in washing plant wastes.

2/ Represents wastes of remaining mineral mining and processing industries - 20 percent of the total wastes generated.

3/ NA - Not available.

TABLE 2. PRODUCTION OF ALUMINA IN 1963 BY ORIGIN AND PLANT

Bauxite Long tons x 10^3 dry basis	Domestic	British Guiana	Dominican Republic	Haiti	Jamaica	Suriname	Other
	Arkansas 1478	335	729	396	5,239	2,518	21
	Ala. & Ga. 47						
Total 10,695	1525						

Alumina Capacities Long tons x 10^3	Sherwin, Texas	Hurricane Creek, Ark.	Bauxite, Ark.	Pt. Comfort, Texas	Mobile, Ala.	Burnside, La.	Baton Rouge, La.	Gramercy La.
Total 5,340	876	803	420	750	865	345	850	430

(from Pincus, 1968)

In their present state many of the mud lakes represent an economic and environmental liability. The high water content of the settled muds reduces storage capacity, and a breach in the dikes can result in inundation of surrounding areas with a caustic mud slurry. The feasibility of dewatering and stabilizing the muds plus reclaiming the land at existing disposal sites is uncertain because very little is known about the engineering properties and behavior of the muds. The safe abandonment and reclamation of future disposal sites is likewise questionable under current mud management and disposal practices.

B. OBJECTIVES OF RESEARCH

The research program on red muds undertaken by the Civil Engineering Department of the University of Michigan has the following main objectives:

1. To determine index and engineering properties which are important in assessing the feasibility of dewatering, stabilizing, and reclaiming the red muds.
2. To analyze alternative methods of dewatering and consolidating red mud deposits for purposes of
    - a) safe abandonment of the mud lakes
    - b) potential occupancy and use of the disposal sites
3. To examine how well various consolidation theories and models predict the behavior of red mud.
4. To determine the suitability of red mud as a borrow material in compacted structural fills or as a reservoir lining material.
5. To recommend the most promising in-situ dewatering and stabilization procedure and the necessary changes in tailings handling and disposal practices.

C. EXPECTED BENEFITS OF RESEARCH

The nature and magnitude of the red mud disposal problem were outlined previously. Many of these problems will only be solved as the result of laboratory and field research programs such as those outlined herein. Expected benefits or payoffs from the research include:

1. Minimizing disposal costs by development of guidelines for efficient tailings management and disposal systems.
2. Maximizing storage by dewatering of impounded tailings.
3. Reclaiming tailings for use as an engineering construction material (e.g., structural fill or subbase).
4. Reclaiming disposal sites for future occupancy and other land uses.
5. Meeting environmental and safety standards related to:

a) Stability of tailings impoundments

b) Ground and surface water contamination

c) Dusting

d) Landuse conflicts

D. SCOPE OF REPORT

The interim nature of this report is emphasized. It is intended primarily as a review of past work and as a description of the research work in progress. A comprehensive analysis of the consolidation and dewatering characteristics of red mud will follow in the final project report and in a doctoral dissertation on this topic.

The testing program described herein is being carried out on red muds from two Alcoa plants (Mobile and Point Comfort respectively), however, this report is confined primarily to test results obtained on the Mobile muds.

The laboratory testing program is a "parametric variation" type of study on reconstituted samples of red mud rather than on in-situ samples. Difficulty in obtaining representative, undisturbed samples from the mud lakes plus other considerations explained later in the report favored this approach. Important parameters varied in the laboratory testing included mud/sand ratios, total solids, dissolved solids, pH, time, and mud type (or source).

The importance of physico-chemical properties— specifically the dissolved solids content and pH of the mud — should be emphasized at the outset. Engineering properties, e.g., shear strength and compressibility, change radically as the dissolved salts are leached from the red muds. Previous studies appear to have overlooked this aspect of the geotechnical properties of red muds.

II. REVIEW OF PAST WORK

A. PROPERTIES OF RED MUDS AND SIMILAR TAILINGS

The engineering properties of red muds have been investigated by Pincus (1968) and Jenny (1973). Pincus was more interested in the composition and physical properties of red muds with a view to recovery of byproducts (e.g., iron) **and** to incorporation of red mud into manufactured products (e.g., Portland cement). Jenny, on the other hand, focused on the geotechnical properties of red muds. His work is reviewed in some detail because of its relevance to the present study.

Representative chemical and minerologic analyses of the red muds investigated by Pincus are shown in Table 3. Silica, alumina, and iron oxide are the major constituents of red muds with lesser amounts of calcium and sodium. Loss on ignition values averaged about 12 percent thus indicating the presence of carbonate in the muds. The mineral composition was described by Pincus as a complex compound of soda, alumina, silica and water similar to noselite in composition. The crystalized constituents detected by x-ray diffraction were predominantly iron oxides (hematite with minor goethite) and remnants of calcite and a hydrated alumina.

Jenny (1973) performed his tests on a red mud from an alumina processing plant in Wilhemshaven, Germany. At time of sampling the plant was processing a mixture of bauxites from Sierra Leone, Jugoslavia, and Australia. His grain size tests showed the material to be a ferro silt with a sand content of 40 per cent. The material had low plasticity (LL=42, PI=14) and was classified as an ML (low plasticity silt) under the USCS system.

Drained, direct shear tests on samples of red mud yielded high angles of internal friction. The entire tailings (which contained 40% by weight sand) exhibited a maximum angle of internal friction of 39° and a residual value of 36°. The sand fraction, on the other hand, exhibited values ranging from 37° to 43° depending upon porosity. Undrained shear strengths measured with a vane apparatus showed strength varying from 0.2 to 1.0 Kg/cm^2 depending upon prior

TABLE 3. REPRESENTATIVE ANALYSES FOR RED MUDS

Ore	Domestic Ore	Imported Ores			Brown Mud
		Source 1	Source 2		
			Suppliers Analysis	IITRI Analysis	
Al_2O_3	26.5	19.1	13.	20.0	6.4
Fe_2O_3	10.7	38.3	52.5	49.0	6.1
SiO_2	22.9	9.3	3.5	3.4	23.3
CaO	8.1	5.3	7.5	6.8	46.6
Na_2O	11.8	6.4	2	0.5 to 5.0	4.1
TiO_2	3.3	6.7	0.X	4.5	3.0
P_2O_5	-	1.0	1	0.8	-
SO_3	2.8	-	0.5	tr.	0.5
L.O.I.	12.9	11.0	12	13.1	7.3

from Pincus (1968)

TABLE 4. GRADATION AND COMPRESSION CHARACTERISTICS OF IRON ORE TAILINGS FROM LABRADOR, CANADA (after Guerra, 1973)

TAILINGS SOURCE	INITIAL CONDITIONS		GRADATION			COMPRESSION BEHAVIOR	
	Water Content (%)	Dry Density (pcf)	% sand	% silt	% clay	Comp. Index, Cc	Coef Consol cv(cm^2/sec)
Knob Lake	33	94	18	79	3	.075	?
	15	121	18	79	3	.012	?
Carol Lake	26	104	90	10	0	.035	2x10^{-3}

consolidation stress. Sensitivity was also fairly high in the vane tests with measured ratios of approximately 5. The results of these shear strength tests are reproduced in Figures 1 and 2.

Jenny studied the dewatering (dehydration) characteristics of red mud by both compression and dessication tests. For unknown reasons, critical compression parameters, viz., coefficient of compressibility, compression index, and coefficient of consolidation, were not reported. Dessication was observed to be slow because of a low permeability of only 10^{-7} cm/sec. A graph summarizing the moisture-density relations for the red mud from Wilhemshaven under compaction, consolidation, and dessication respectively is shown in Figure 3.

Maximum dry density during dessication (89 pcf) occurred at a water content of 37.5 percent. This water content is the shrinkage limit of the mud. This water content (or dry density) also corresponds to a suction (negative pore water pressure) of 8 $\mathrm{Kg/cm^2}$. This is the effective confining stress which must be exceeded in order to increase the dry unit weight above 89 pcf by static, one-dimensional compression.

Unfortunately, Jenny did not report the composition of the pore fluids in his red mud samples nor did he appear to perform any experiments on leached samples. The concentration of dissolved solids or salts in the red mud can significantly affect engineering properties such as compressibility and shear strength. This oversight tends to limit the usefulness of Jenny's findings.

Pettibone & Kealy (1971) and Hamel & Gunderson (1973) studied the geotechnical properties of mine tailings. The former investigations presented data on the properties (e.g., grain size, shear strength, and relative density) of tailings from nine mining and mineral extraction operations in the USA. Most tailings were shown to have requisite properties for subbase and structural fills when properly compacted and emplaced. Pettibone and Kealy gave examples of the use of tailings in two civil engineering projects.

Hamel & Gunderson presented data on the shear strength of silt size tailings (slimes) from a gold mine in South Dakota. In spite of their small particle size the slimes had a relatively high shear strength which increased with increasing density. This high strength was attributed to particle interlock and to attractive electrical forces between layer-lattice mineral particles.

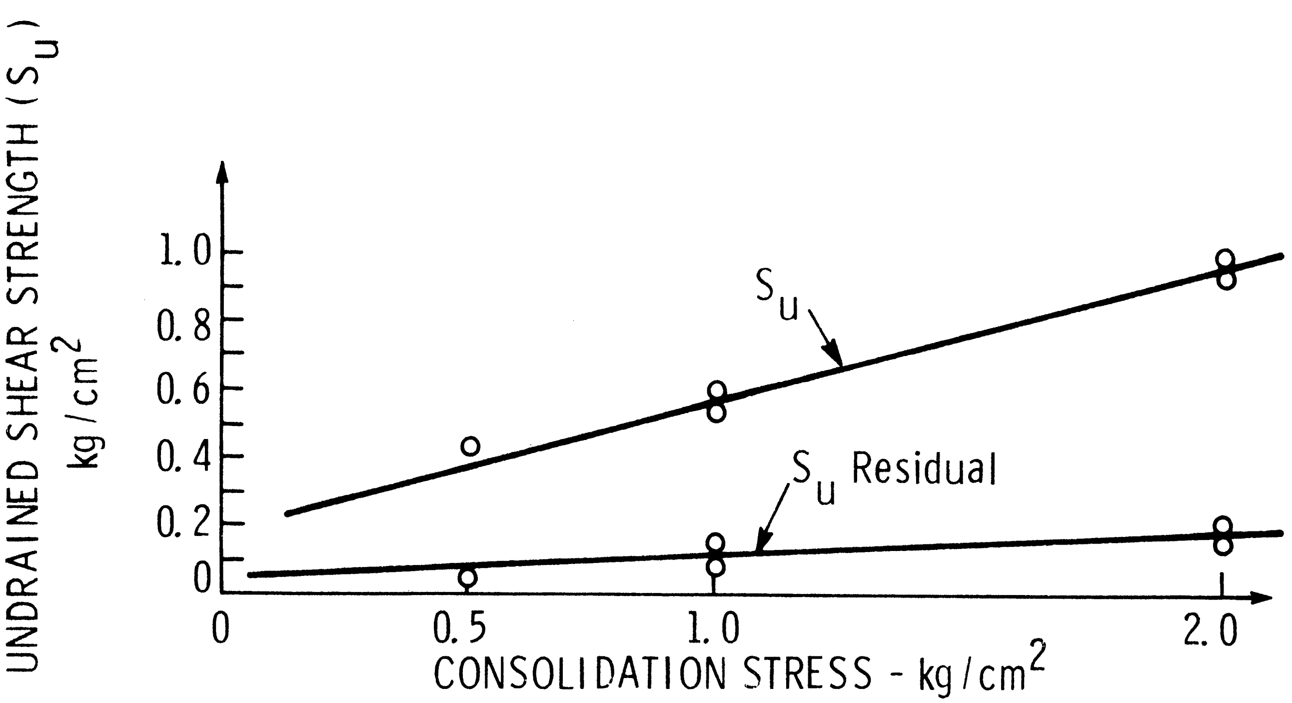


Figure 1. Undrained shear strength of ferrosilt (red mud) from Wilhemshaven, Germany (from Jenny, 1973)

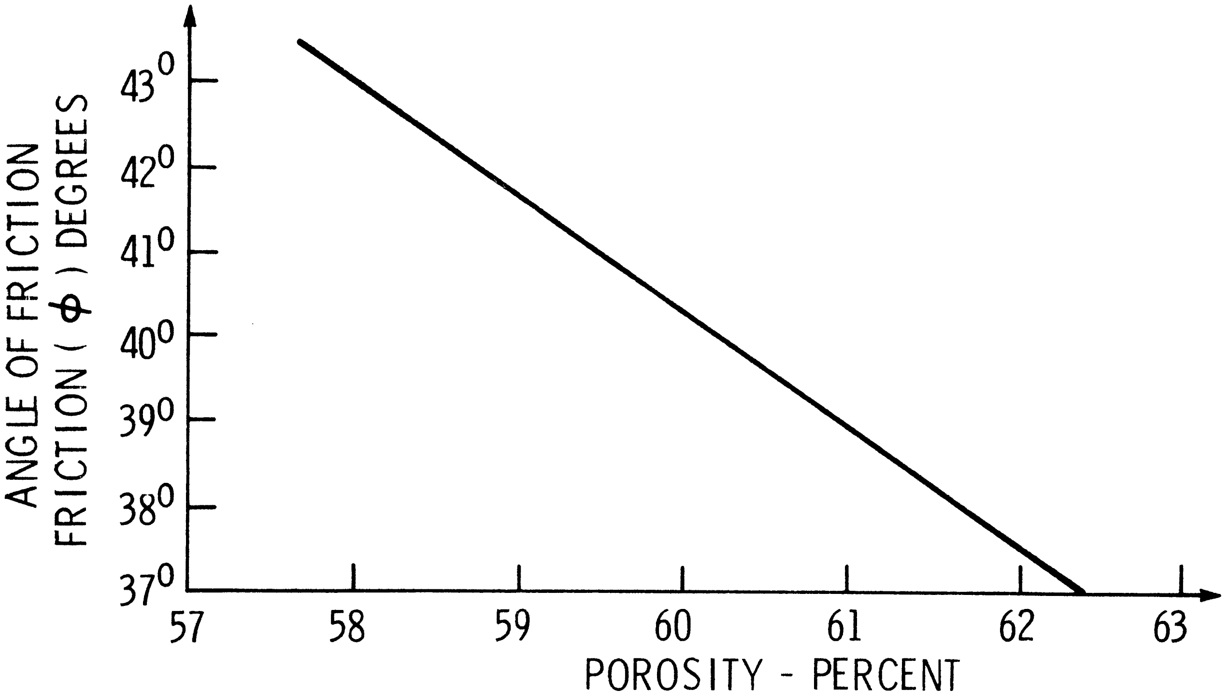


Figure 2. Effective angle of internal friction of ferrosilt-sand from Wilhemshaven, Germany (from Jenny, 1973)

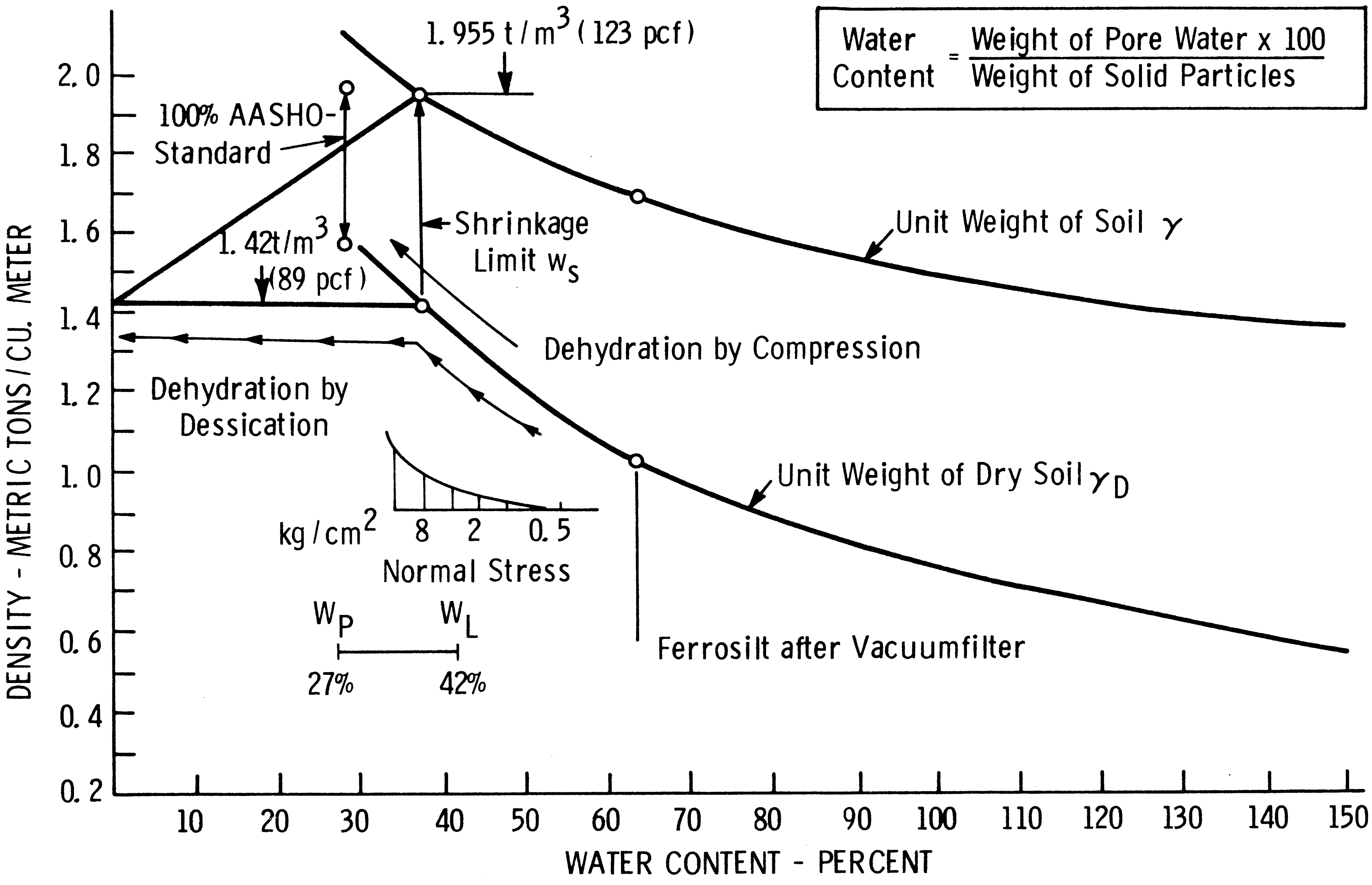


Figure 3. Moisture-density relationships under dessication and compression respectively in ferrosilt from Wilhemshaven, Germany (from Jenny, 1973)

Guerra (1973) obtained both mineralogic and geotechnical data on iron ore tailings from Labrador, Canada. Geotechnical data was obtained on essentially two types of tailings, viz., silt size tailings from Knob Lake and sand size tailings from Carol Lake. Consolidation tests were run on the Knob Lake tailings at initial (presumably settled)dry densities of 94 and 121 pcf and initial dry densities of 104 pcf for the Carol Lake tailings. Results of gradation and compression tests on these two size ranges of iron ore tailings are summarized in Table 4. Both types of tailings were described as non plastic.

Guerra concluded from his tests that sand-size, iron ore tailings had the requisite properties to permit their widespread use as engineering construction material. Silt size tailings, on the other hand, were difficult to compact and were found to be susceptible to severe erosion and frost action. Guerra advised against the use of these tailings for the construction of tailings dams.

Perhaps the most significant finding of all these studies on tailings was the unexpectedly high values of shear strength and angle of internal friction. Potential problems with sensitivity and liquefaction of the fine grained fractions of the tailings were alluded to but not investigated in detail.

B. TAILINGS IMPOUNDMENTS

The design, construction, stability, and maintenance of tailings impoundments and structures (dams) have been discussed in detail by several investigators. References cited in this report include technical articles by Smith (1969, 1973), Miners (1973), Brawner and Campbell (1973), D'Appolonia(1973), and Johnston (1973). Virtually all of these articles were published in the Proceedings of the 1st International Tailings Symposium held in Tucson, Arizona in late 1972.

Miners (1973) specifically described Alcan's experience with disposal of red mud tailings from a plant located at Arvida, Quebec. Increased production over the years required the disposal of more then 2,000 tons per day of tailings in such a way as to eliminate dusting or leakage problems associated with ponding operations.

Alcan's current mud disposal system consists of pumping the mud as a slurry (15-30% solids by weight) to local ponds with a pond water recovery system near the processing plant on a year-round basis. It also includes a dredging operation in the local ponds during the warm weather months to remove the settled mud, separate the coarse fraction, and pump the fines some six miles through a 14-inch diameter pipeline to a much larger settling basin.

Most above ground tailings disposal facilities described in the technical literature fall into one of three categories, viz., side hill, cross valley, or stock pile deposits. Side hill disposal areas are the most common type of layout (Smith, 1969) because of the natural advantage of gravity flow, without the disadvantage of river diversion usually needed for tailings ponds formed behind cross-valley dikes. Stock piles, which are placed on relatively level ground, require four retaining dikes and the effluent generally has to be pumped up into the disposal area.

There are several ways of discharging tailings into an impoundment. Spigotting by means of a perimeter discharge leads to a gravity separation of the tailings with the coarser fraction being deposited next to the dike where they are needed to improve stability of the structure. Another alternative is to use cyclone classifiers on the mud discharge lines. The cyclones separate the sand fraction from the remainder of the fine tailings (or slimes). This cycloned sand can then be used for construction of the dikes. A perimeter discharge system using cyclones is shown in Figure 4.

The dikes themselves can be constructed by three basic procedures: upstream method, dowstream method, and composite upstream/downstream. The upstream method is employed in conjunction with spigotting and requires the least amount of sand of the three methods. The downstream method requires fairly large quantities of cycloned sand or other suitable borrow material and generally results in dikes which are the most stable of the three. The composite method is a compromise between stability and sand availability. Each of these construction methods is schematically shown in Figures 5 to 7.

D'Appolonia (1973) stressed the need for careful design of tailings disposal facilities in order to permit safe abandonment. Principal technical considerations cited by D'Appolonia are staged construction, the use of available materials to provide safe economical retaining embankments, and the control of normal- and storm water runoff to reduce embankment pore pressures.

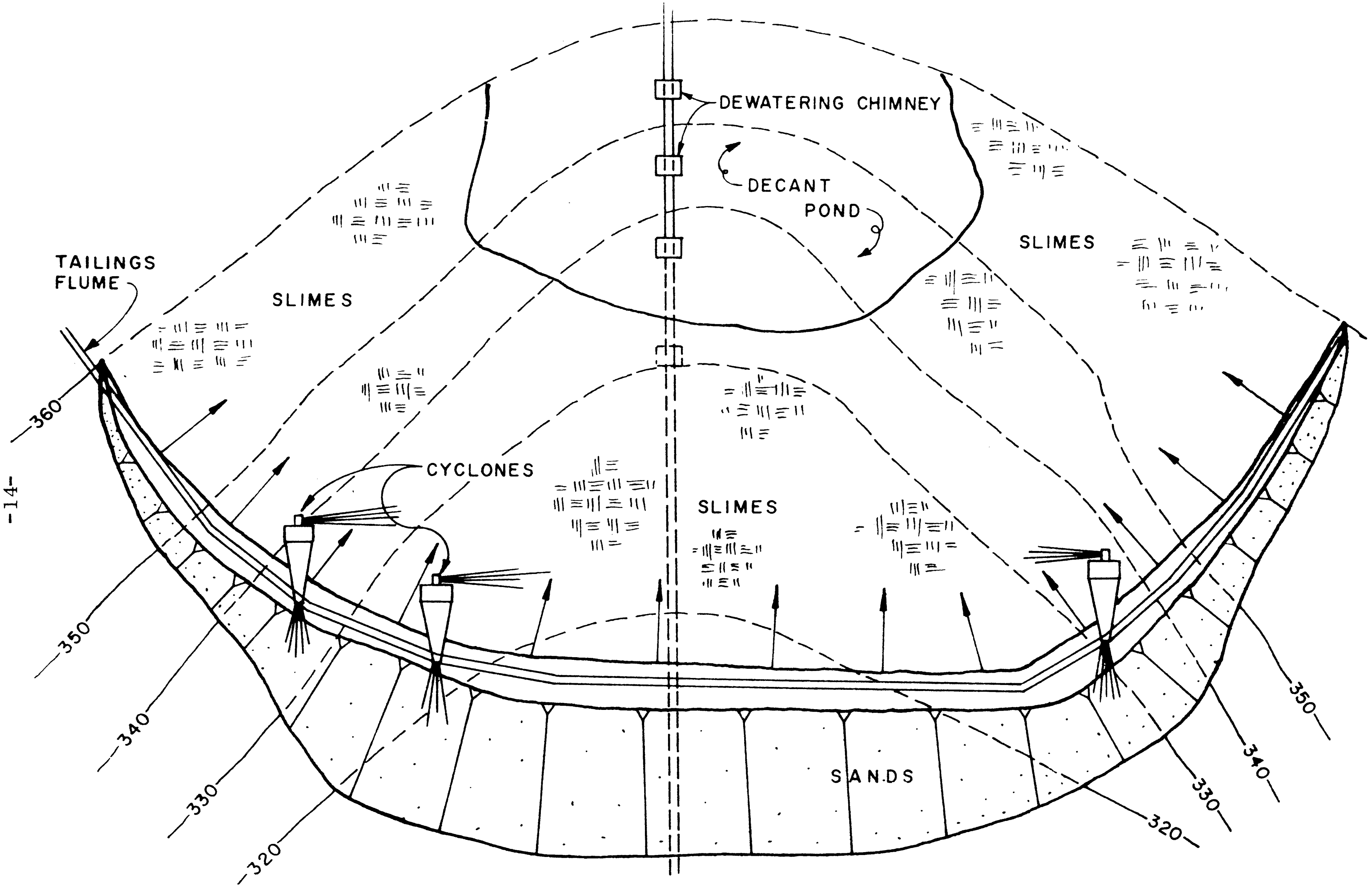


FIGURE 4. **PERIMETER DISCHARGE WITH CYCLONES** (after Smith, 1969)

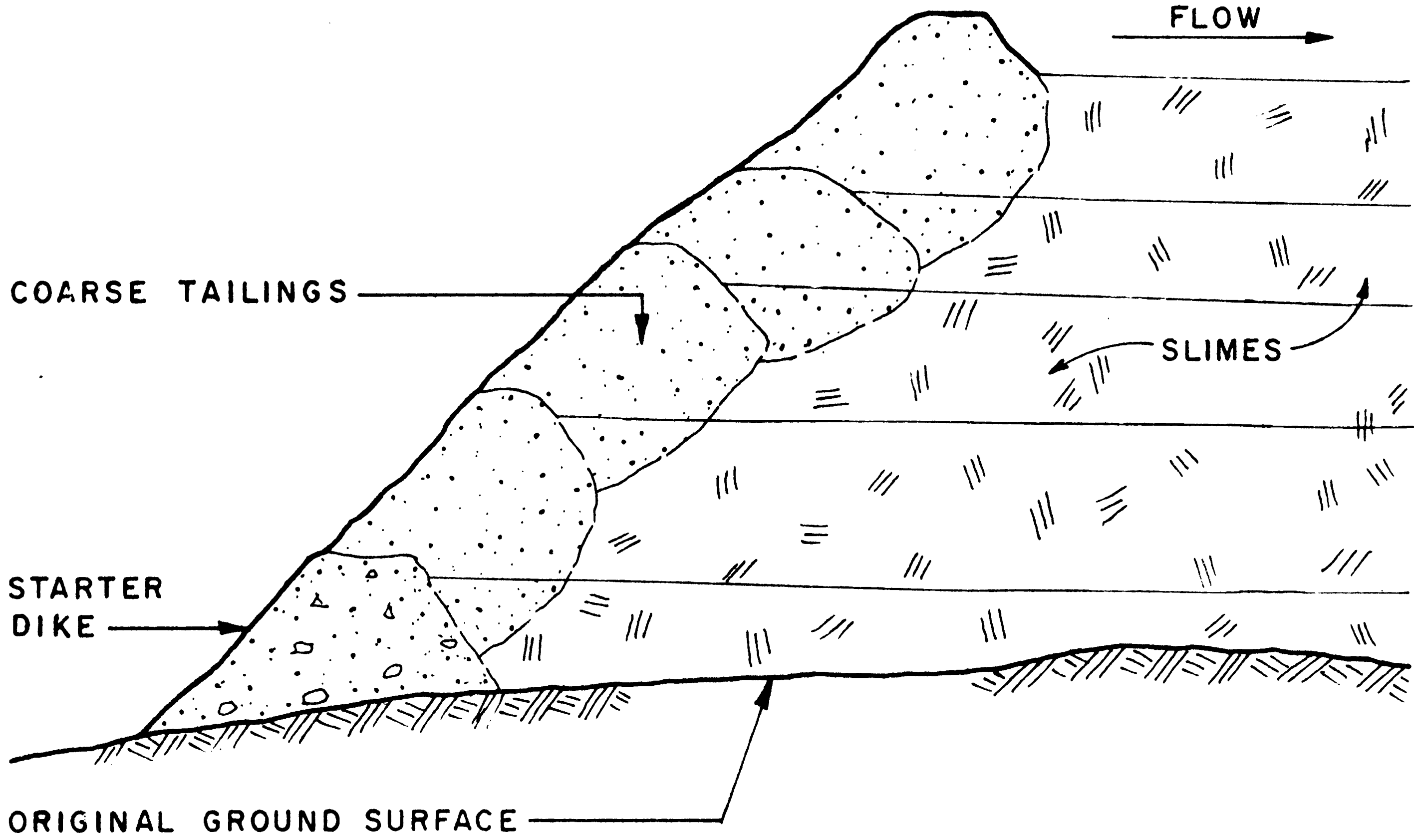


FIGURE 5. **UPSTREAM METHOD DIKE CONSTRUCTION** (after Smith, 1969)

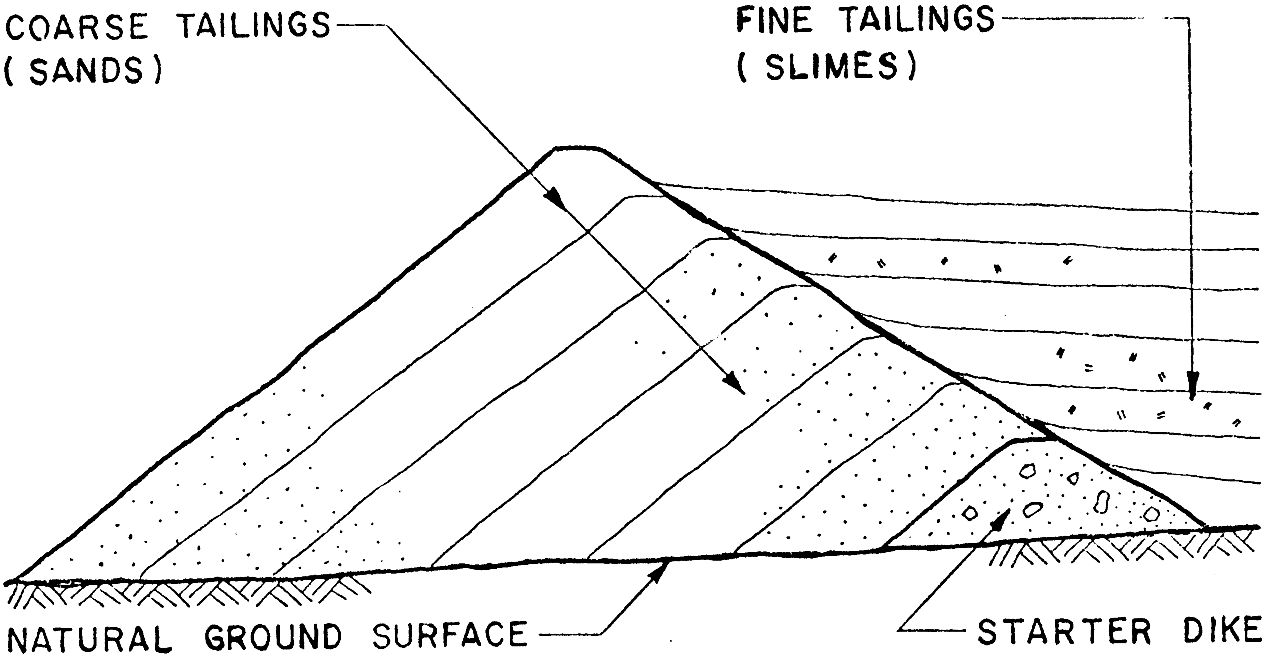


FIGURE 6. DOWNSTREAM METHOD DIKE CONSTRUCTION (after Smith, 1969)

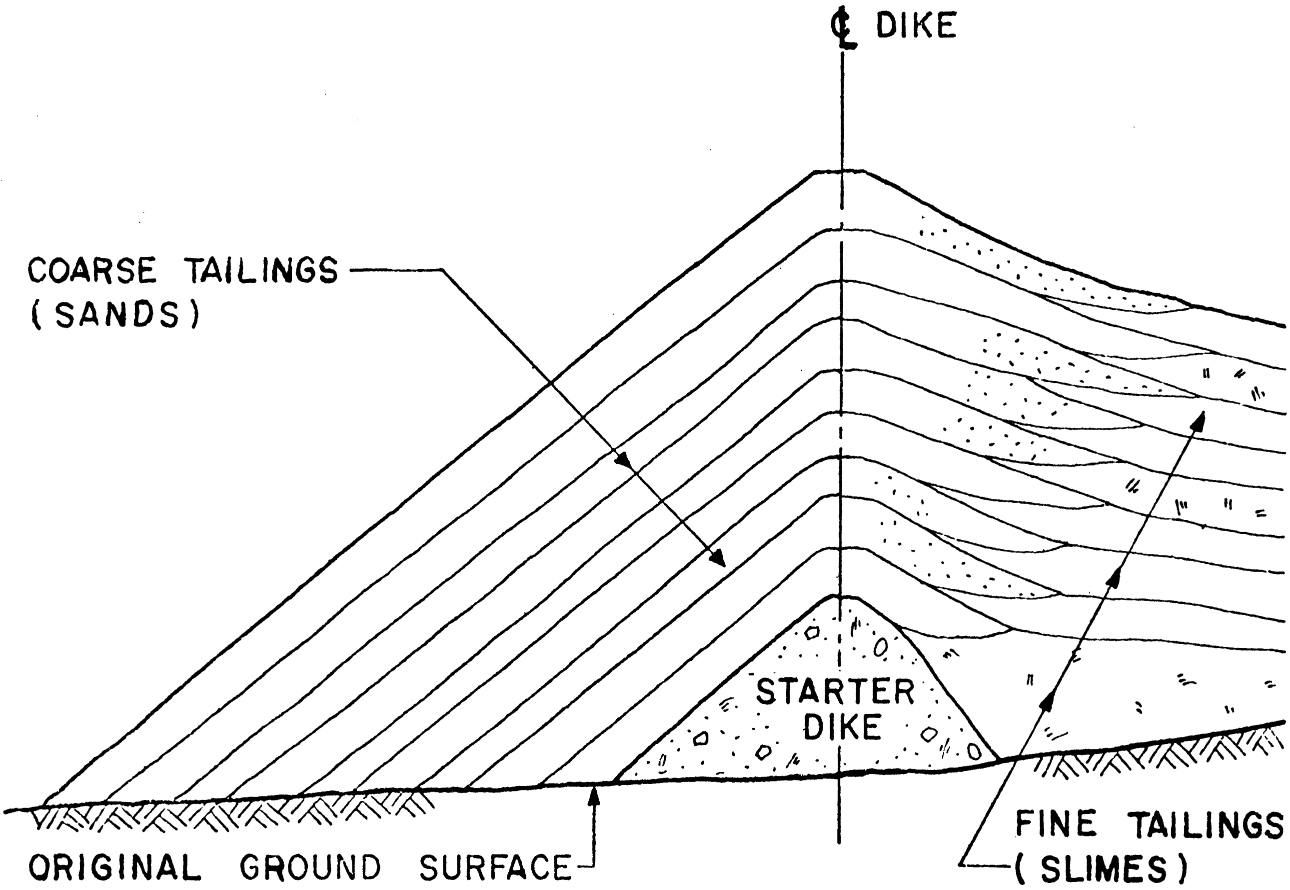


FIGURE 7. COMPOSITE UPSTREAM/DOWNSTREAM DIKE CONSTRUCTION (after Smith, 1969)

Johnston (1973) considered the problems of tailings disposal on the basis of operating costs for each part of a typical disposal system. The various parts which need to be considered and analzyed include slurry thickening, slurry transport, tailing containment, seepage control, tailing treatment, effluent transport, and area restoration. Johnston outlined a systematic procedure for evaluating each of these factors thereby making it possible to select the optimum tailings management and disposal system.

C. TECHNIQUES FOR IN-SITU DEWATERING

Dewatering of tailings deposits and impoundments is a critical requirement for stabilization and reclamation of disposal sites. Swaisgood and Toland (1973) provide a good overview of the water balance or budget (inputs and outputs) in a tailings impoundment. This water balance is shown schematically in Figure 8. The inputs include runoff, precipitation, and slurry (or make up) water. In diked, stockpile type impoundments typical of Alcoa's Point Comfort and Mobile operations run off is insignificant; the major input in this case is water in the mud slurry itself.

The outputs include evaporation, decantation, and drainage (or seepage). Evaporation or dessication provides the most economical method of reducing pore pressure and increasing density of fine tailings. Evaporation, however, is dependent upon climate and is only significant in hot, arid climates where evaporation exceeds precipitation. And even in climatically favorable areas, the rate of production of slimes and the available ponding area may be such that there is not enough time for dessication to occur before the next layer of tailings is deposited. Smith (1969) has outlined a possible way around this difficulty by using compartmented impoundments with sequential deposition of tailings as shown schematically in Figure 9. Decantation is aided by tailings which have good settling or flocculation properties. Chemicals or other compounds added to the slurry for this purpose (e.g., starch) may be costly on the scale which would be required. The final alternative or vehicle for removal of water is drainage and seepage. Drainage can be hastened or enhanced by both compression and interspersal of drains or perveous drainage boundaries in or around the mass to be dewatered.

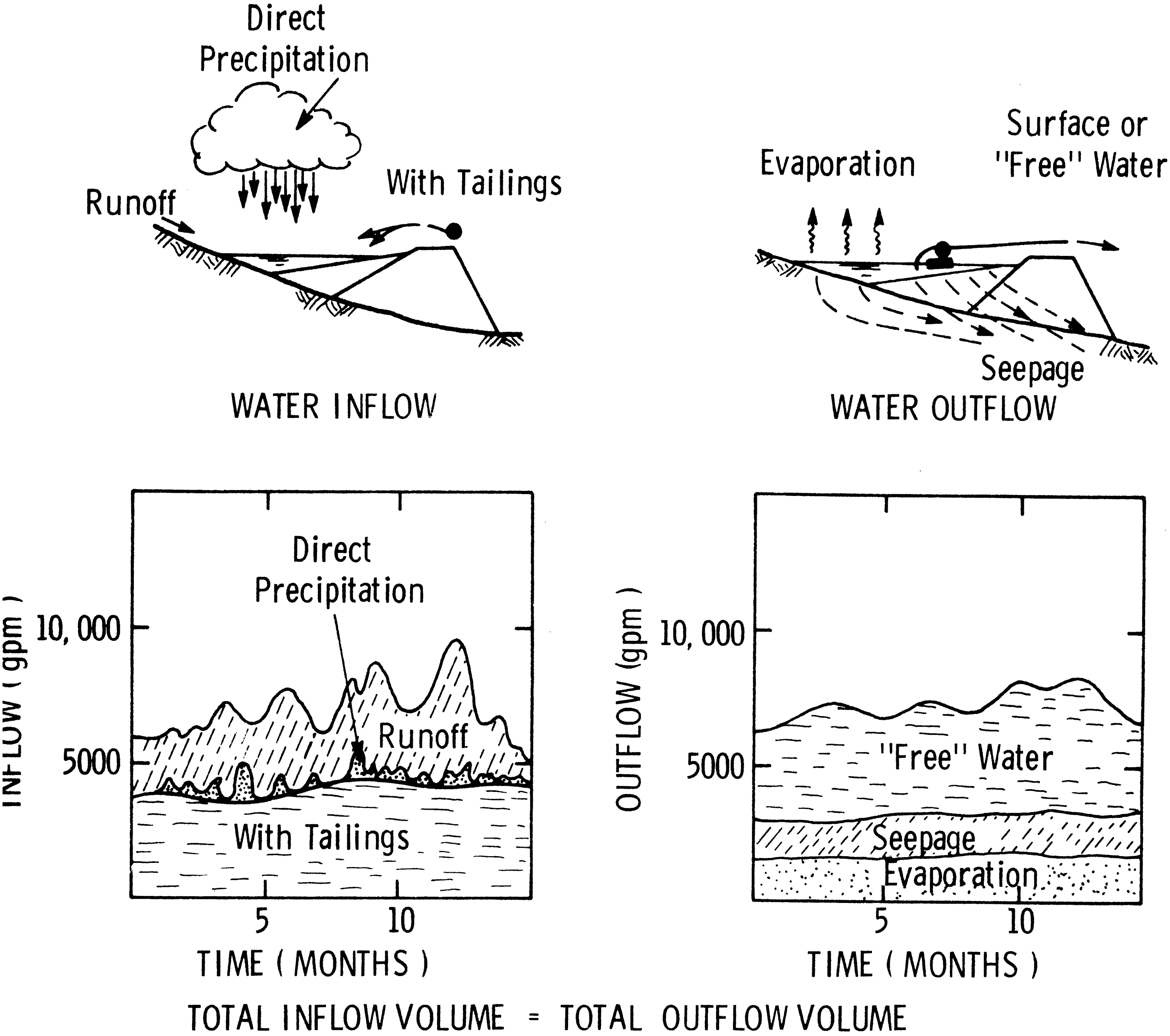


Figure 8. Water budgets in a tailings impoundment (after Swaisgood & Toland, 1973)

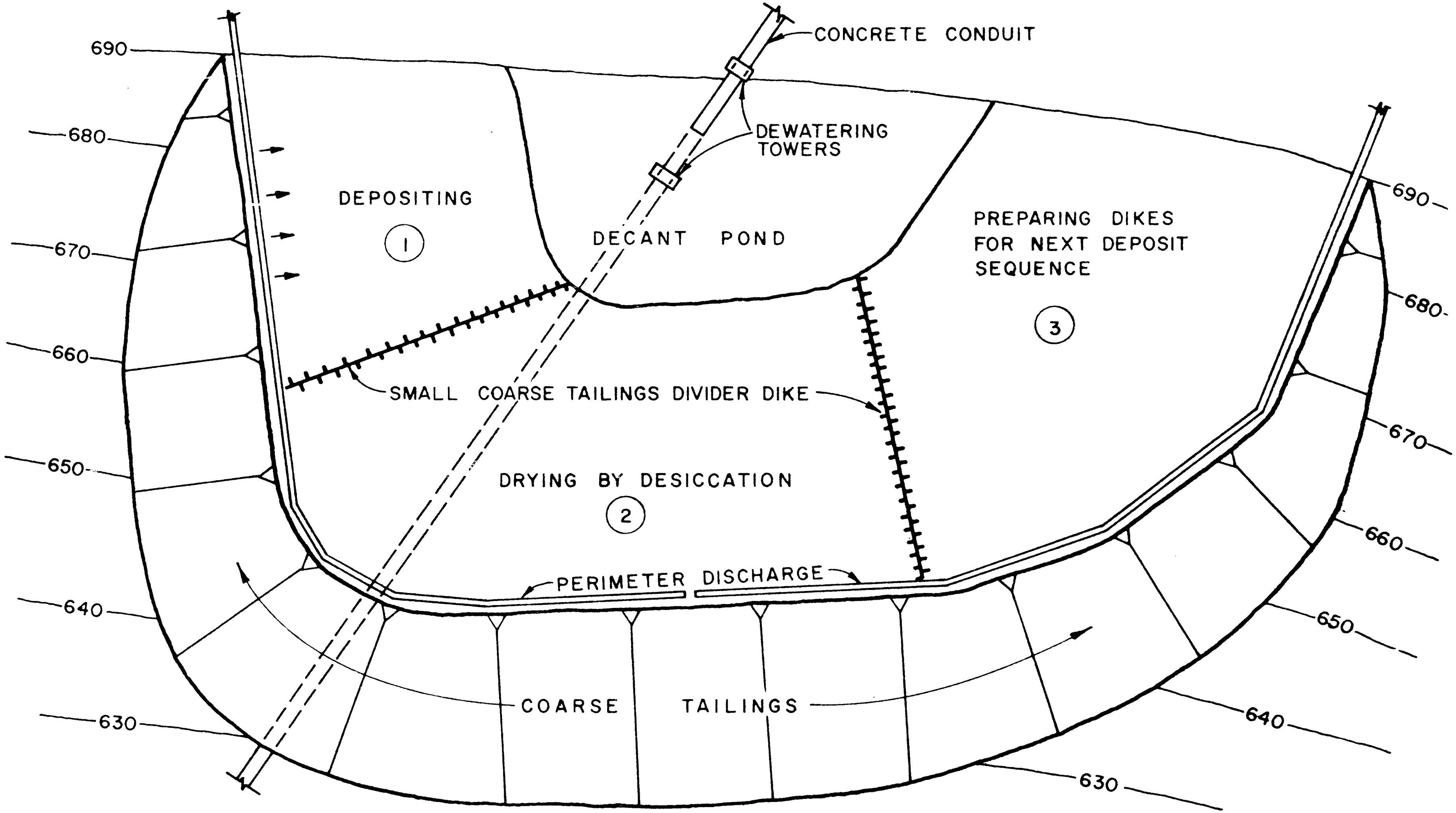


FIGURE 9. **SIDE HILL DEPOSIT WITH POND SUBDIVISIONS** (after Smith, 1969)

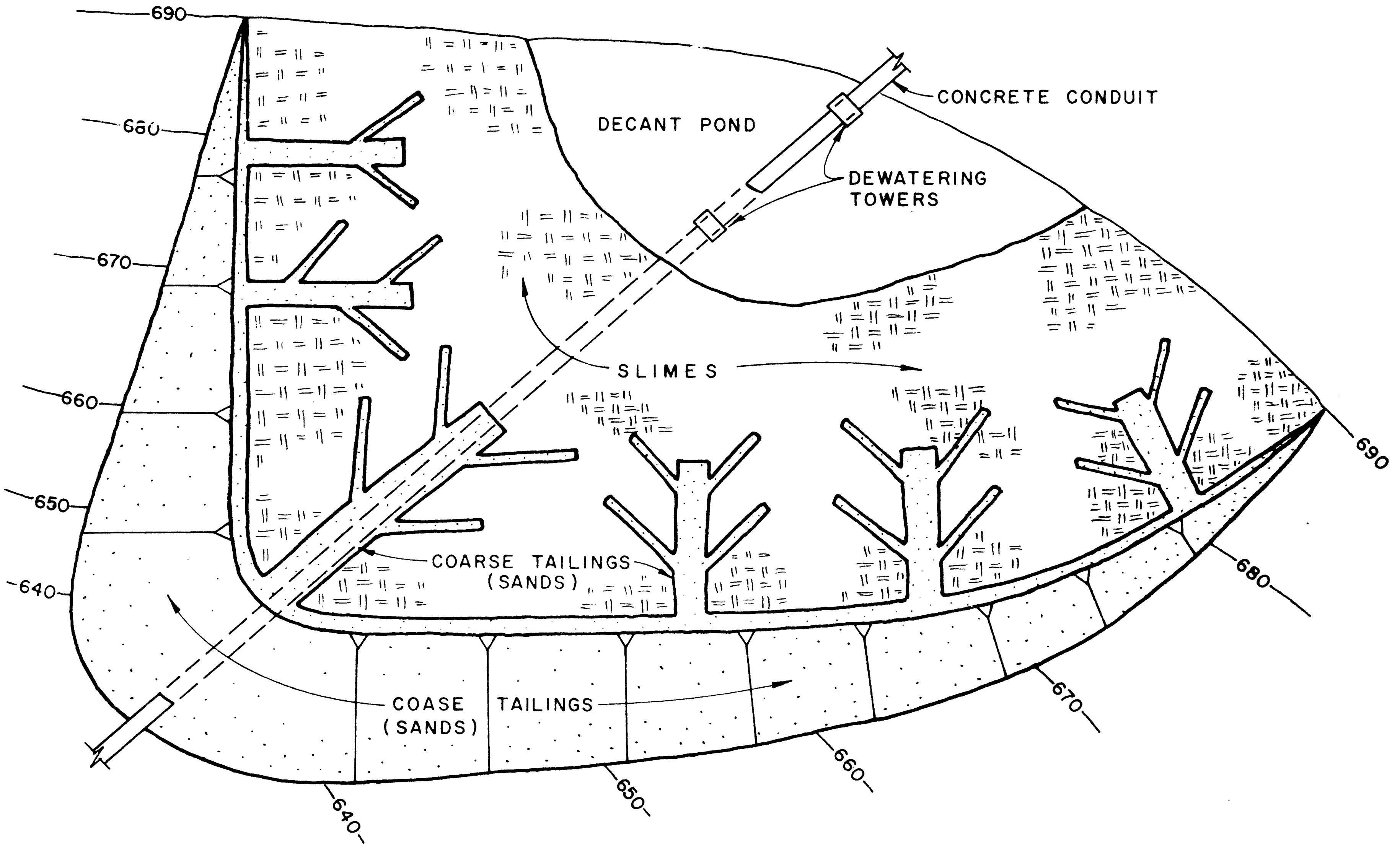


FIGURE 10. - **HERRINGBONE DRAINAGE FINGERS** (after Smith, 1969)

These drains may consist of one or a combination of the following:

1. Horizontal sand drainage blankets — vertical drainage
2. Vertical sand drains or fibre wicks — radial drainage
3. Composite sand-crushed rock drainage fingers

Smith (1969) described a finger drain system for use in a comparmented tailings impoundment. This system is schematically shown in Figures 10 through 11.

Precompression or surcharging is a well established procedure in geotechnical practice for dewatering and consolidating soft, compressible soils and sediments. Rutledge (1970) has described compression techniques for dewatering and consolidating marginal wet lands.

In precompression or surcharge stabilization, the weight of an imported sand fill acts to squeeze water from the soil voids, thereby giving the soil greater shear strength and minimizing post construction settlement. The sand fill also acts as a perveous drainage blanket. This technique has been used to consolidate and stabilize soft estuarine or lake bed clays up to 70 feet thick. Sand fills used for this purpose may reach heights up to 30 feet and be left in place for periods ranging from several months to several years.

Consolidation or dewatering can be speeded up considerably by using vertical sand drains (radial drainage) in conjunction with surcharge. Johnson (1970) has reviewed the state of the art of precompression with vertical sand drains. The time required to reach a given degree of consolidation with vertical sand drains depends primarily on sand drain spacing and the coefficient of consolidation of the material. Once the compression characteristics of a material are known, it is then possible in principle to design a surcharge-drain system to achieve a required degree of consolidation in a given interval of time.

Surcharge or preloading can also be provided by the weight of water. This technique offers several advantages over a sand fill, e.g., faster construction time and elimination of requirements for handling and disposal of large quantities of sand fill. In the case of tailings impoundments the mud slurries or slimes themselves could be used as a surcharge. The use of water surcharging to stabilize and dewater tidal marsh deposits consisting of up to 20 feet of highly compressible organic silts and peats has been described

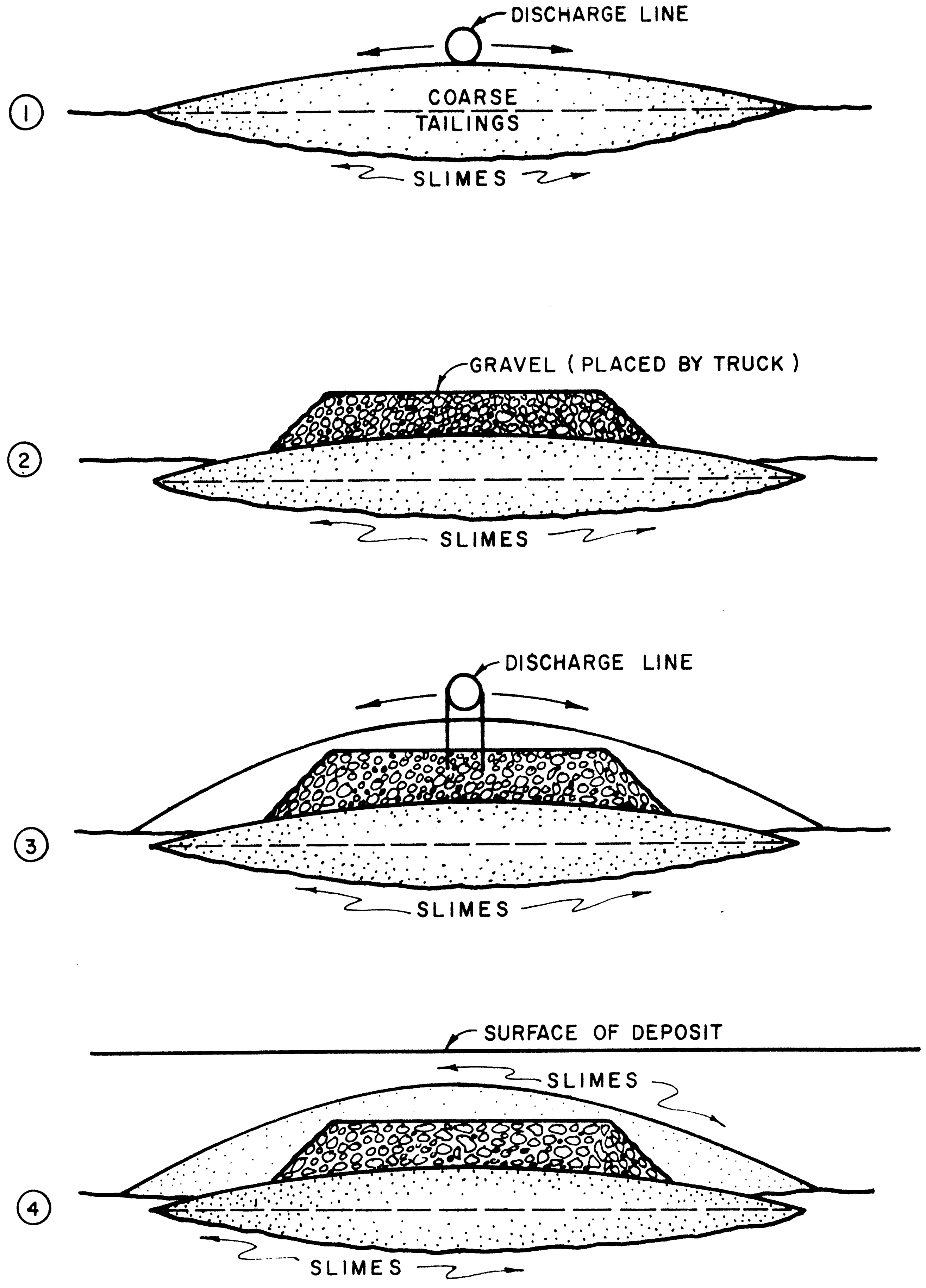


FIGURE 11. **CROSS-SECTION OF ZONED DRAINAGE FINGER** (after Smith 1969)

recently by Tozzoli and York (1973). In using this method a thin, 10 mil (0.25 mm) PVC membrane is normally employed as a barrier between the surcharge water and the pore water in the underlying compressible material. In order for this method to work it is essential to minimize leakage of surcharge water through the membrane, otherwise the weight of the overlying water becomes ineffective as a surcharge loading.

Still other procedures for dewatering of fine tailings have been reported by Vogt (1973) for red muds produced by Kaiser Aluminum plants at Baton Rouge and Gramercy, Louisiana. Development studies at these two sites showed that neither evaporation nor decantation sufficed to dewater and consolidate "as is" impoundment of red mud slurries. After processing, the bauxite tailings contain a substantial fraction of fines which have a particle size in the range of 1 micron. When flocculated with starch the effective diameter increases to 10 microns. Even so, the resultant slurry at 15 to 20 percent solids has very poor settling characteristics. The maximum in-situ consolidation for such a slurry was reported to be 28 to 30 percent solids by weight. This is far below the solids content required for reclaiming and returning the tailings disposal site to other uses after ultimate filling.

Pilot field studies conducted at the Gramercy plant led to development of three promising methods for dewatering and stabilization of red mud tailings, viz.,

1. Rotary drum filtration/lake pumping and distribution
2. Shallow DREW Process (decantation, drainage, and evaporation of water)
3. Deep DREW Process

Of the three processes, the Deep DREW was selected for the Gramercy plant. The reasons for selection were: the feasibility of achieving a stable* land storage material of 50% solids or greater; minimum land area requirements; minimum energy requirements; lowest capital and operating costs of the three processes developed.

The salient features and conclusions for the two DREW processes are quoted directly from Vogt's report:

---

*A precise definition of stable was not given in the report. No shear strength data as a function of water content was provided, for example.

A. Shallow DREW Process

1) Successive distribution of 4 inch layers of red mud at a feed concentration of 15-20% solids over a sand drainage bed resulted in consolidation to as high as 95% solids by drainage and evaporation
2) Uniform distribution of the slurry was practical over 2.3 acres from a single feed manifold
3) Cycle times for this process varied from 11 days to 45 days with an average of 19 days. Cycle time is defined as the time required to reach a water content corresponding to the shrinkage limit(60 to 70% solids by weight) at a depth of 4 inches
4) Repetitive feedings of such drainage beds are possible without affecting the performance of the process. Thirteen such feedings were conducted.
5) Land area requirements are greatest with this process. Some 600 acres of sand drainage beds alone are required to meet Gramercy plant's mud flow (2400 TPD).

B. Deep DREW Process

1) Dewatering of red mud in deep layers (18 feet of slurry mud at 18% solids over a porous sand bed) by a combination of decantation, drainage and evaporation will result in a consolidated mud mass of 50% solids. The dewatering sequence is shown schematically in Figures 12 and 13.
2) Continuous dewatering accounts for a 50% volume reduction during the feeding stage. Decantation removes all rainfall and the largest fraction of mud slurry liquid during the feeding and most rainfall throughout the life of the bed (65% of total). Subsurface drainage provides free liquid removal during the feeding and shortly thereafter (35% of total). These relationships are shown schematically in Figure 14.
3) Subsequent percolated rainfall is removed via drainage. Evaporation becomes the principle dewatering mechanism after the free liquid is removed. Evaporation must be implemented by rapid rainwater removal in order to reach the ultimate 50% + solids content
4) The costs of land area usage, energy and operation are minimized with the Deep DREW Process. Impoundment area reclamation appears

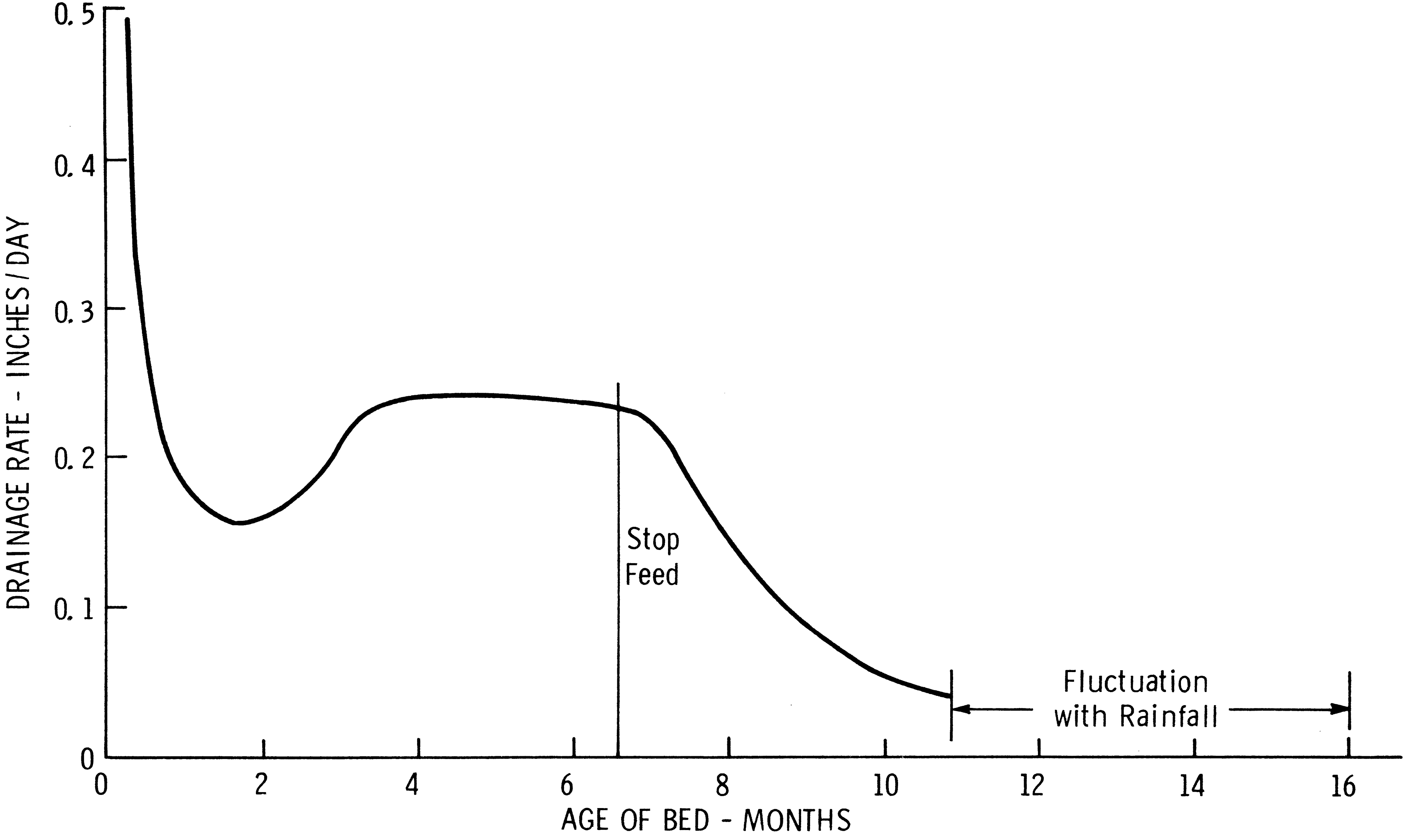


Figure 12. Drainage rate vs. bed age, Deep DREW Process (from Vogt, 1973)

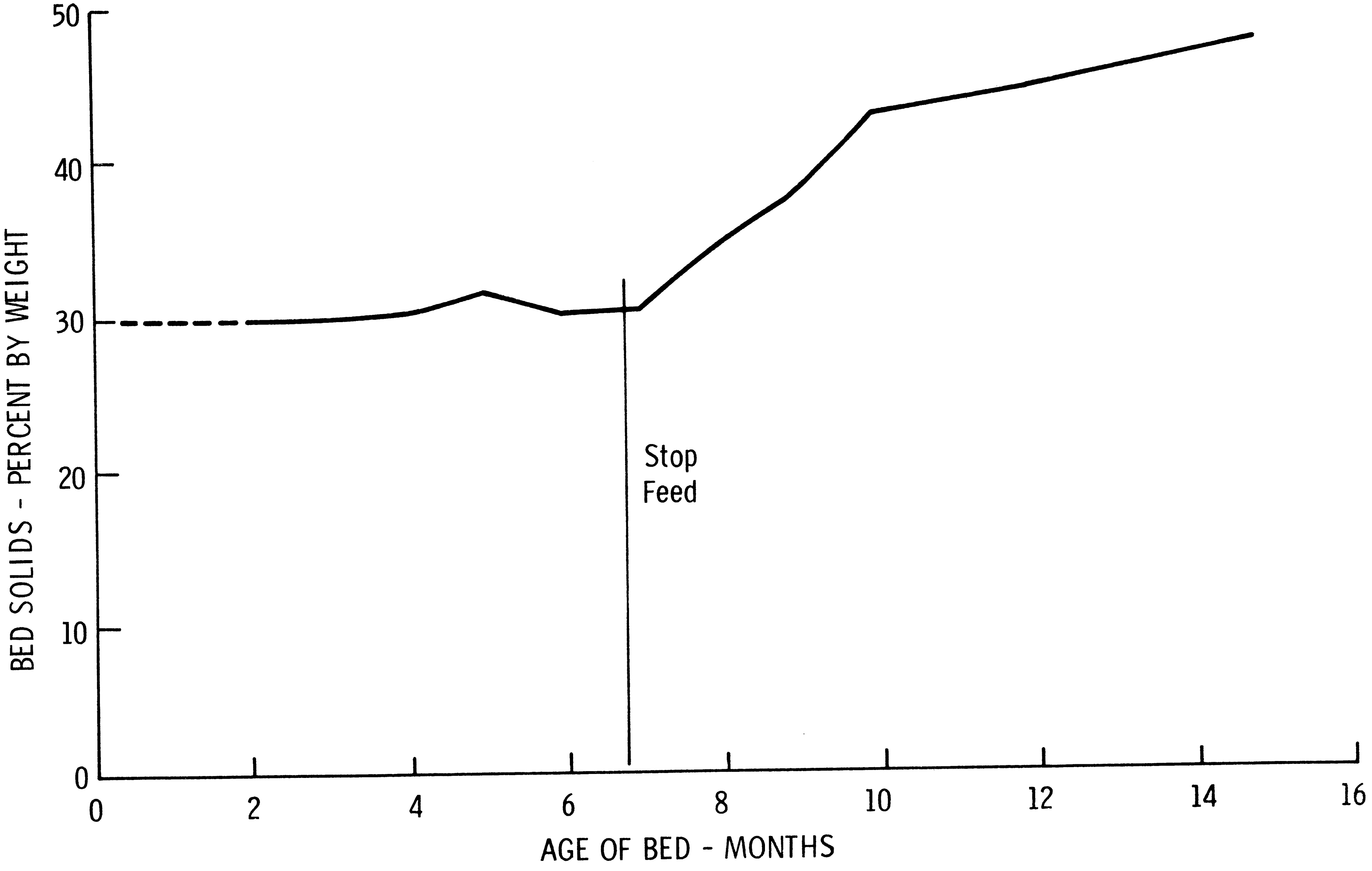


Figure 13. Average bed solids vs. bed age. Deep DREW Process (from Vogt, 1973)

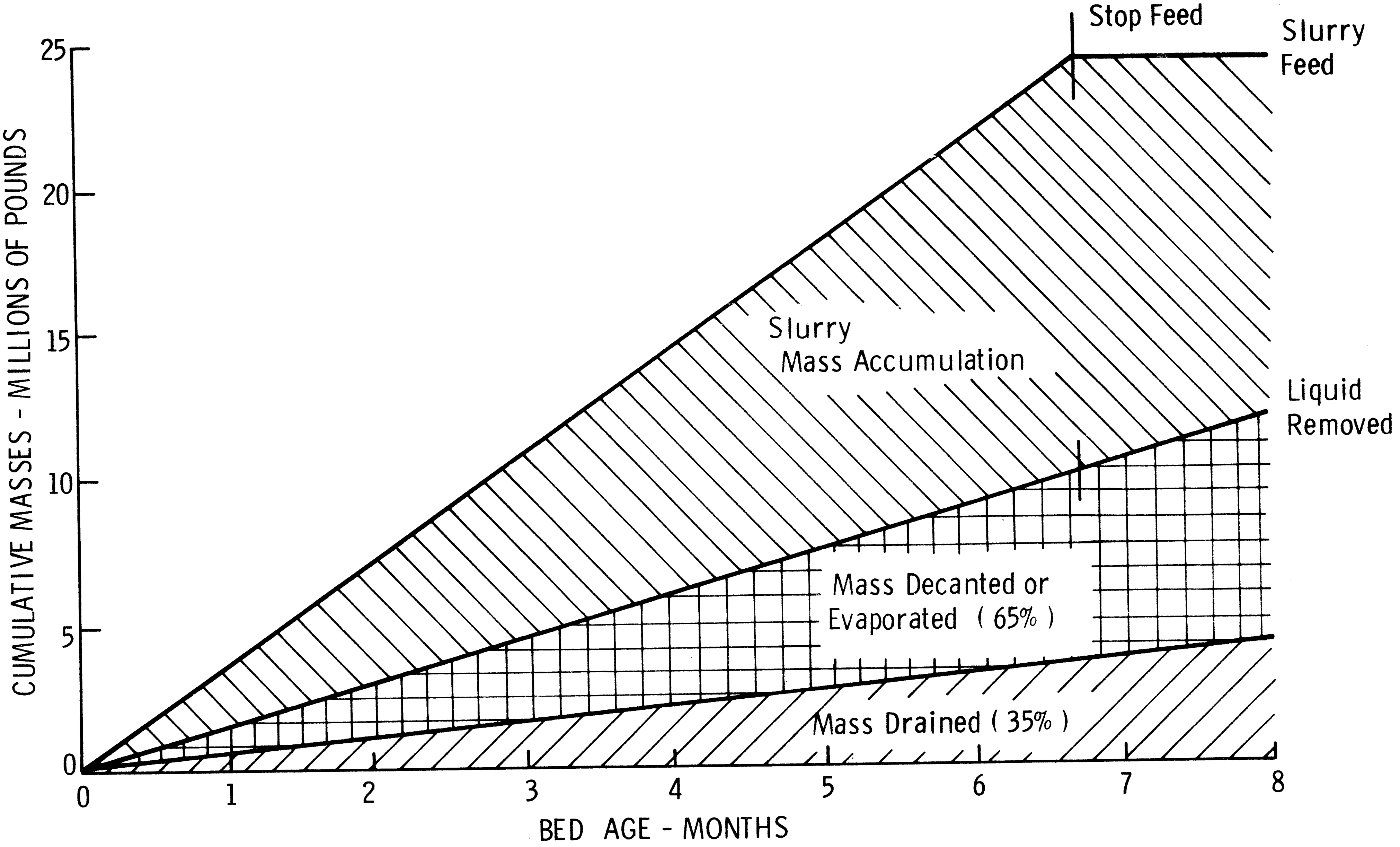


Figure 14. Loss or accumulation of water and slurry mass vs. bed age, Deep DREW Process (from Vogt, 1973)

likely.

The possibility of dewatering and consolidating the red muds still further, i.e., in excess of 50% solids, by precompression was not studied or at least not reported by Vogt for the Kaiser aluminum red muds.

D. CONSOLIDATION THEORIES AND MODELS

In Soil Mechanics, the term consolidation refers to the change in volume of a soil mass subjected to a quasi-static loading. Saturated soils or impounded mine and mill tailings can be considered two-phase systems, consisting of individual solid particles (usually of crystalline nature) and pore fluid (usually water). Both of these constituents are virtually incompressible at the load intensities normally applied in practice. Therefore, upon application of load, there is very little immediate deformation, and the load is supported by the fluid. Depending on the existing boundary conditions, a certain hydraulic gradient is established which initiates flow of pore fluid from the soil mass. The escape of fluid produces a decrease in pressure within the remaining pore fluid. Since the applied load remains constant, there must be a transfer of stress from the fluid to the soil or mineral skeleton. The amount of stress transferred to the soil skeleton is defined as the effective stress because it is that portion of the total applied stress which is effective in producing volume change of the soil mass.

The rate of flow of pore fluid is a function of the remaining fluid pressure within the soil. Since this pressure constantly decreases due to the escape of fluid, the rate of flow and the rate of transfer of stress to the soil or mineral skeleton constantly decrease. In addition, the time required to transfer the applied stress from the fluid to the skeleton depends upon the ease with which the fluid can travel through the soil mass. After all of the applied load has been transferred to the soil skeleton, there is continued deformation, probably due to the rearrangement of soil particles. This phenomenon has been termed secondary compression, whereas that portion of consolidation which occurs during hydraulic flow is referred to as primary consolidation.

In general, consolidation is a three-dimensional process. When a soil mass is loaded, water flow and the accompanying change in dimensions occurs in all directions. While three dimensional analyses of elastic materials are possible and practical, they are extremely complex for inelastic, inhomogeneous, anisotropic materials such as soils or similar particulate systems. Therefore, most consolidation theories, particularly the earlier ones, dealt only with the case of one-dimensional consolidation, in which the flow of water and the deformation of soil occur in only one direction, usually the vertical. The existence of this condition depends on the geometry of both the load and the loaded area, and does occur to some extent in many practical problems. A good example of the one-dimensional condition is the case of a uniform surcharge placed over a large area of compressible soil of uniform thickness or a tailings deposit in a diked impoundment.

The first consolidation theory was presented by Karl Terzaghi in 1925. This theory dealt with only the one-dimensional primary consolidation of saturated soils, and treats the magnitudes and rate of settlement as separate entities. Both the pore water and the soil particles are assumed to be imcompressible. The stress-strain relation of the soil skeleton is assumed to be a linear, time independent one. Darcy's Law is assumed valid in describing the flow of fluid. Homogeneity is assumed, thereby requiring only one stress-strain and velocity-gradient relationship to describe the entire soil mass. The strains, velocities and stress increments are assumed to be small, permitting a quasi-static theory.

Based on the above assumptions, the strains induced by a load are directly preportional to the change in effective vertical stress, which, at any time, is equal to the excess pore water pressure already dissipated. Therefore, the rate of consolidation should be exactly described by the rate of dissipation of excess pore water pressure, which is given by a partial differential equation of the diffusion type. If, in this equation, a further assumption is made that the coefficient of permeability remains constant during consolidation, the classical consolidation equation is obtained.

Based on many years of use, the Terzaghi theory has been found to predict the magnitude of settlement quite accurately, but in general, to overestimate the time required to attain that settlement. This is probably due to the assumption of one-dimensionality. Since some lateral yield does in fact occur in almost every case, consolidation will proceed more rapidly thaan predicted.

The two major reasons for the general acceptance of the Terzaghi theory are the numerous years of its successful use and its mathematical simplicity. Due to the mathematical simplicity, improved solutions can be obtained by varying some of the parameters about which simplifying assumptions have been made. Richart (1957) has solved the consolidation problem numerically considering a variable void ratio. Schiffman (1960) considered the case of variable coefficient of permeability. Lo (1961) attempted to take into account the variablity of the coefficient of consolidation. Schiffman and Gibson (1964) have considered the effect of the depth variation of the coefficients of permeability, compressibility and consolidation.

One of the major drawbacks of the Terzaghi theory is its assumption of linear stress-strain behavior. Raymond (1965,66,69) attempted to improve the theory. He found that Terzaghi's theory predicted slower rates of pore water pressure dissipation than were actually measured in oedometer tests and in natural thick clay layers. Using two experimental findings, namely that for many soils there exists an approximately linear relationship between void ratio and the log of effective stress and between void ratio and the log of permeability, Raymond derived his general equation of one-dimensional consolidation. This equation predicts pore water pressure dissipation in the field and in oedometer tests performed at large load increment ratios more satisfactorily than Terzaghi's theory.

Recently, quite a few viscoelastic theories have been presented which take into account both non-linear stress-strain relationships and simultaneous primary and secondary consolidation. Many of these theories utilize, or can be described in terms of, linear or non-linear rheological models. Rheological models, while yielding 'non-linear shaped' stress-strain curves, are termed mathematically linear or non-linear, depending on the validity of superposition. The major rheological elements which have been used in various combinations to model soil behavior are the Hookean elastic body(spring), the Newtonian viscous liquid (dashpot) and the Kelvin body (spring and dashpot in parallel).

Two of the consolidation theories utilizing linear rhelogical models were proposed by Gibson and Lo (1961) and by Wahls (1962). Gibson and Lo model soil behavior by a Hookean Spring connected in series with a Kelvin element. The Hookean spring reacts immediately to the application of effective stress, but the deformation of the Kelvin element is retarded by the dashpot, which sustains the total load. As the load in the dashpot is relieved, effective stress builds up gradually from zero to the full value of applied stress, accompanied by the deformation of the two springs.

Wahls models soil response by a number of rheological units in series, each unit consisting of a dashpot in series with a Kelvin element. The dashpots model secondary behavior, while the Kelvin elements describe primary consolidation.

Barden (1965) describes the effective stress-strain relationship of soil by a single Kelvin element, whose dashpot exhibits non-linear viscosity. The major advantage of this non-linear theory is its applicability to any sample thickness or load increment ratio. However, it seems to either overemphasize the viscous effects during primary consolidation, or underestimate the amount or duration of secondary consolidation.

All of the theories mentioned thus far deal strictly with the one-dimensional case. As previously mentioned, any three-dimensional theory is quite complex. One of the few three-dimensional theories, and perhaps the most mathematically elegant, was presented by Biot (1941). Although the theory is formulated using basically the same assumptions as these made by Terzaghi, Biot introduces the three components of displacement and the excess pore water pressure as time dependent variables, thus allowing a coupled behavior. This leads to the treatment of magnitude and rate of settlement as interdependent entities, and they need not be handled separately. Since there are four unknown quantities (three components of displacement and pore water pressure), four elastic constants are needed to describe the constitutive relations for the soil mass. Two of these deal with the elastic properties of the soil skeleton, and two indicate the influence of the pore fluid. In later years (1955,56,57) Biot refined his theory to include anisotropy of the elastic skeleton, compressibility of the viscous fluid, and the relative velocity between the fluid and soil particles.

A very recent theory, presented by Mitchell, Greenberg and Witherspoon (1973) describes the chemico-osmotic consolidation of soils. When significant differences in salt concentration exist between the fluid within and surrounding a soil mass, chemico-osmotic gradients may be established which are sufficiently high to initiate migration of water and salt. This migration can be described using the posulates of irreversible thermodynamics. This phenomenon was found to be most prevalent in highly compressible, very fine-grained, active soils such as bentonite. The presence of high salt concentration gradients is also required for chemico-osmotic consolidation to be significant. The high dissolved salt content of the impounded red muds enhances chemico-osmotic effects. The extent to which this phenomenon is significant in affecting the dewatering and consolidation behavior of red muds should be ascertained.

III. DESCRIPTION OF ALCOA TAILINGS DISPOSAL FACILITIES AND RED MUDS

A. TAILINGS PRODUCTION

1. Location of Alumina Plants and Source of Ores

The red mud tailings investigated in the present study come from two of Alcoa's alumina processing plants, viz., Point Comfort, Texas and Mobile, Alabama. Both plants are located on the Gulf Coast, however, the climate at Point Comfort is drier. The climate (i.e., the evaporation-precipitation balance) is an important consideration in selecting the optimum dewatering scheme for impounded tailings.

Tailings production from the Mobile and Point Comfort plants are approximately 1000 and 3000 tons per day respectively on a dry weight basis.

The Mobile plant uses only Moengo and Paranam bauxite from Surinam in South America. The mud lake samples and the samples from the mud hoppers or filter presses were both presumably derived from this source. The origin of Point Comfort bauxite is less certain in so far as the mud lake samples are concerned. On the other hand, the samples from the last stage thickner which were sent to the University of Michigan for testing came from a mixture of Carribbean and Australian bauxites.

2. Preparation of Mud Slurries.

The bauxite ore is ground to a minus 10 mesh size; alumina is then leached out by the Bayer process. The residual consists of both fine grained (mud) and sand size tailings. The proportions of mud and sand may vary depending upon the source (or type of ore) and the alumina extraction process.

The fine grained fraction or muds are dewatered at the plant in thickeners or filter presses to an average solids content of 19 percent. The coarse grained fraction or sands are removed by screens or sand traps ahead of time.

At Point Comfort the mud/sand ratio (wet wt. basis) was reported to be 19 lbs. mud/1 lb. sand. Mud from the last stage thickener is again diluted in the mud mixer and discharged to the mud lakes at 12-15% solids.

At Mobile, the mud/sand ratio was reported to average 20 lbs mud/1 lb sand. The range in mud/sand ratio is 7-42. Here sand which is caught in sand traps at the plant is pumped into a classifying screw which feeds the sand into hoppers where it joins the mud tailings caught in filter presses. The mud and sand tailings are pumped together in a dilute slurry to the mud lakes at 9-14% solids (12% average).

B. TAILINGS DISPOSAL

1. Layout and Construction of Mud Lakes

The tailings are pumped as dilute slurries to stockpile type impoundments. These impoundments or "mud lakes" as they are called in the alumina industry are constructed above ground. The size of individual impoundments ranges from 40 to 200 acres. The crests of the dikes reach as high as 100 feet above the ground.

Plan views showing the layout and extent of the impoundments at Mobile and Point Comfort are shown in Figures 15 and 16 respectively. Point Comfort is presently discharging its tailings into a single, large impoundment (Mud Lake No. 4) which has an area of 260 acres and a dike height of 100 feet. Mobile discharges its tailings into a series of smaller impoundments ranging in size from 40 to 60 acres.

The dike construction is quite different at the two plants. At Point Comfort the dikes are constructed entirely from native borrow material (Beaumont clay). At Mobile, on the other hand, the dikes are constructed using sand which is separated and recovered from the red mud tailings themselves. The "downstream method" of dike construction is essentially used in this case. Leakage through the sand dikes is minimized as the fines penetrate and seal off the permeability of the dikes.

2. Discharge Procedure

At Mobile the red mud slurry is discharged into a sand trap adjacent the dikes. The sand is then dredged out periodically and used for construction of the dikes. This procedure is used in lieu of cyclones. The fines (muds) overflow the sand traps and flow out into the mud lakes.

At Point Comfort the sand fraction is not separated from the muds. The entire slurry is disgorged by point discharge or spigotting around the periphery of the mud lakes. The sand fraction tends to settle out fairly quickly forming deltas around the discharge points.

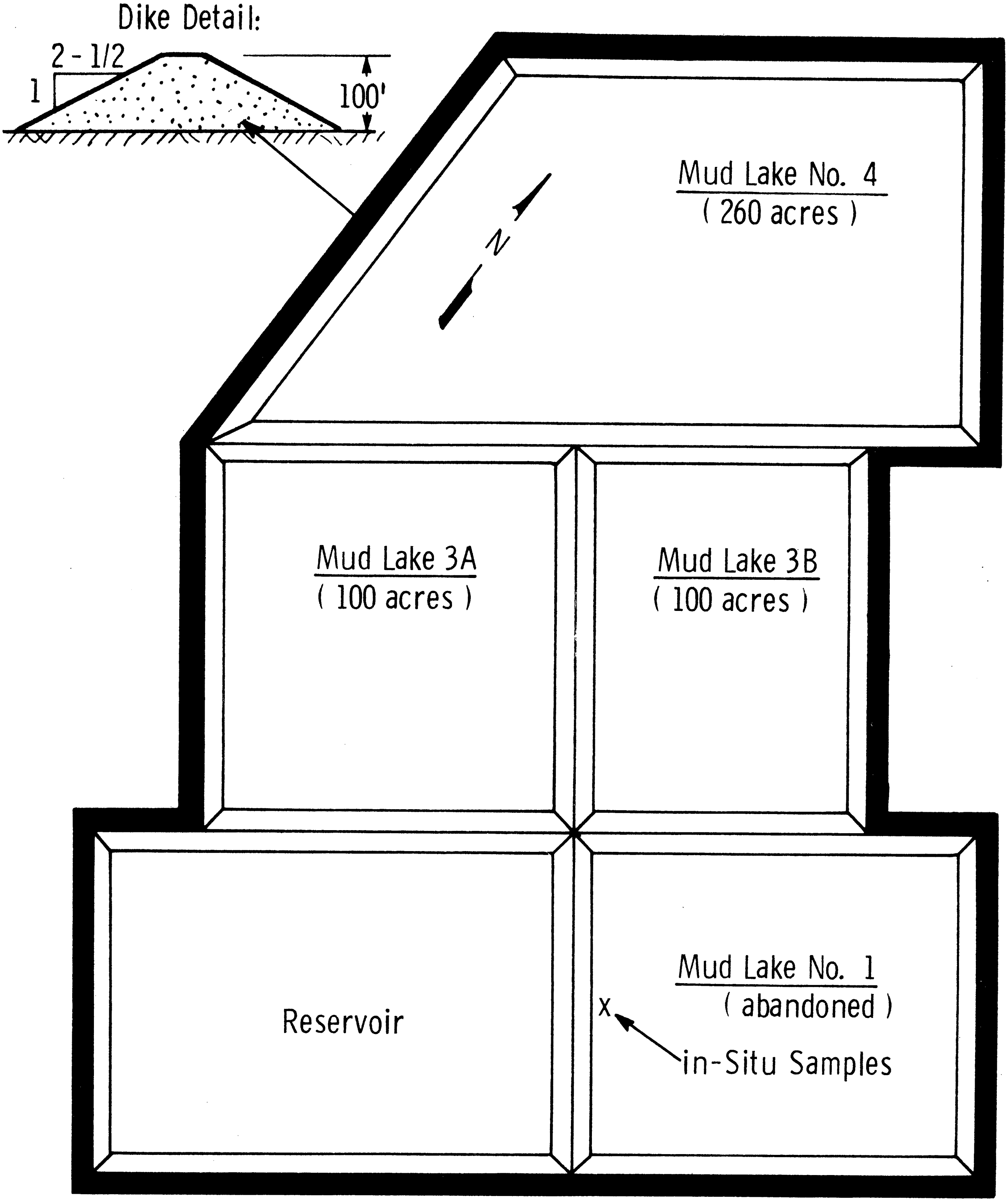


Figure 15. Layout of mud lakes, Point Comfort, Texas

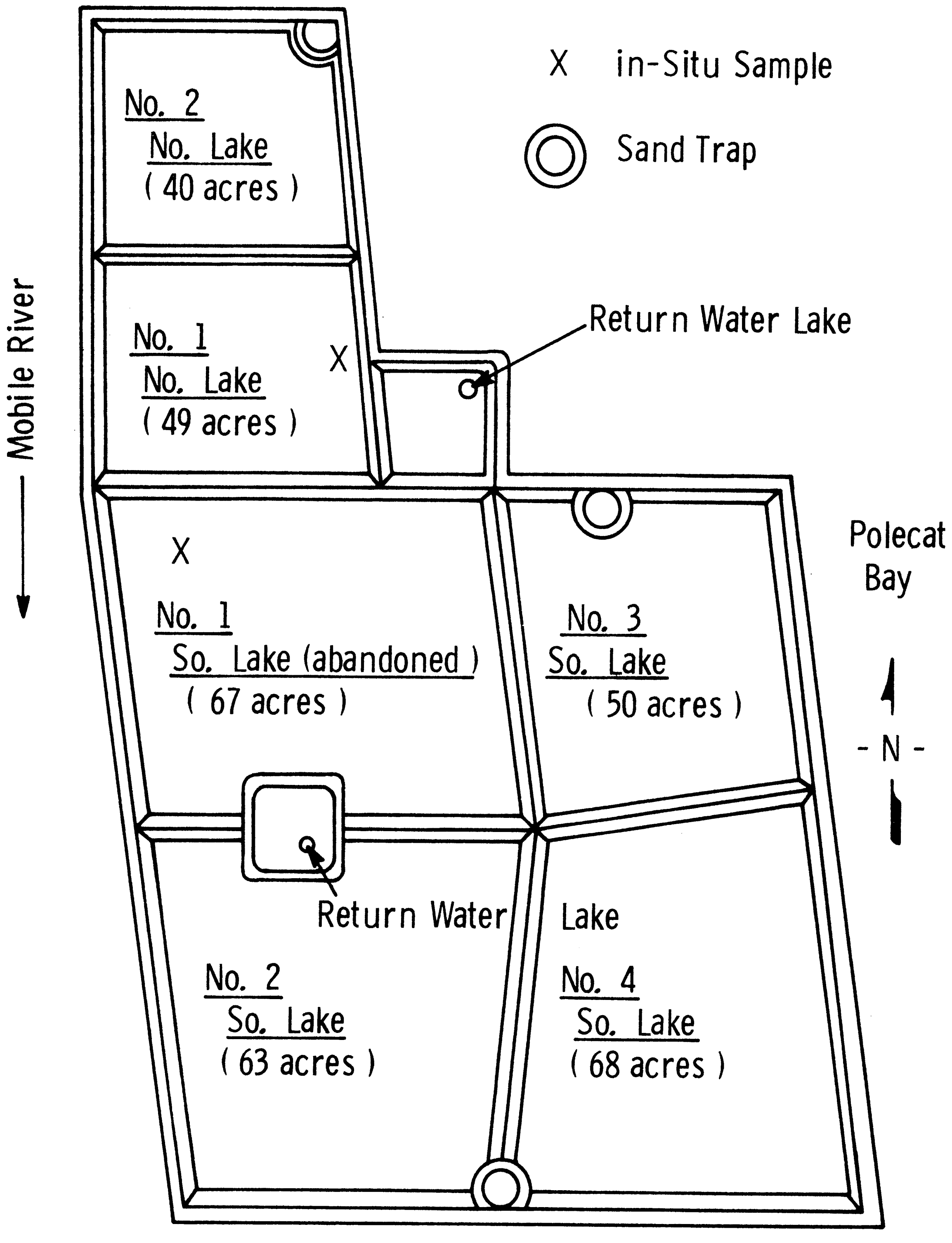


Figure 16. Layout of mud lakes, Mobile, Alabama

C. DESCRIPTION OF RED MUDS TESTED

1. From Mud Lakes

An extensive testing program on in-situ samples recovered from the mud lakes was planned initially. Sampling difficulties precluded this approach. Only disturbed samples were recovered and even these were obtained from shallow depths, near the dikes; hence they may not be representative of the entire mud lake deposits. Consequently, only a limited number of gram size distribution and water content tests were run on the in-situ samples.

Grain size distribution curves for in-situ Mobile and Point Comfort muds are shown in Figures 17, 18 and 19. The in-situ samples from Mobile were obtained from points located 10 and 50 feet away from the dike. The in-situ samples from Point Comfort were obtained from a delta in an abandoned mud lake at a point 80' from the dike. The grain size distribution curves for the total tailings or feed slurry are also shown in Figures 17 through 19 for comparison. The gradation curves for the Mobile muds show that the samples recovered from the mud lakes near the dikes bear little resemblance to the total tailings discharge from the processing plant. These in-situ samples are predominantly sand size material (even though processed through sand traps in the mud lakes) whereas the total tailings are predominantly silt and clay size.

2. From Processing Plants

The vast majority of the laboratory tests were performed on reconstituted samples of red muds coming directly from the processing plants. Mud samples from the last stage thickeners or filter presses were used for this purpose. Sand size tailings from the classifiers were shipped separately and combined with the muds in the laboratory to give different mud/sand ratios. The muds were shipped either as slurries or as a wet filtered mass. Grain size distribution curves for the processing plant tailings are shown in Figures 20 and 21. The curves show the gradation of the tailings from the sand trap, last stage thickener (or filter press), and the total tailings.

A summary of water contents and percent sand for tailings recovered from the mud lakes at Mobile is given in Table 5.

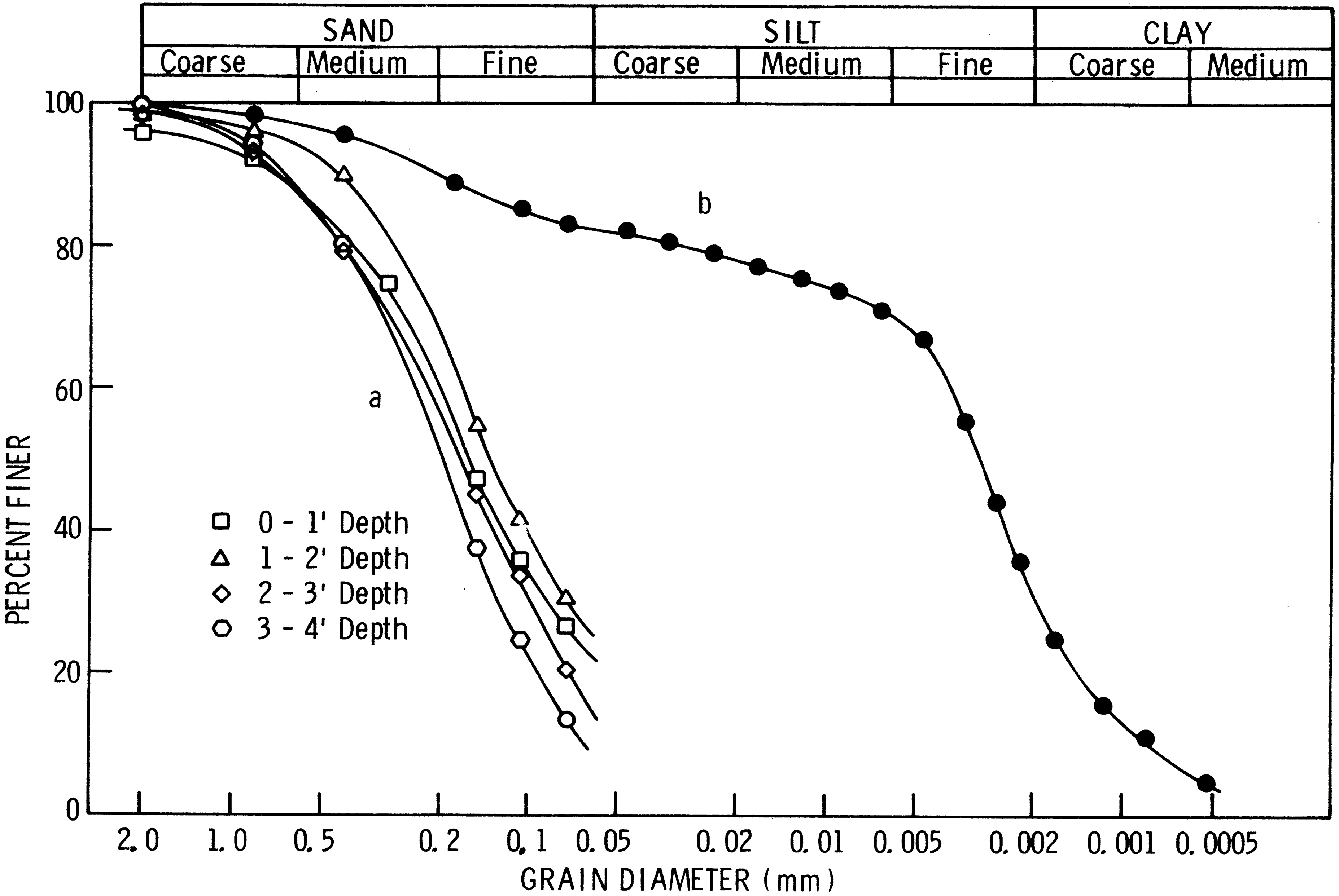


Figure 17. Grain size distribution of in-situ red muds, Mobile, Alabama.
a) #1 North Mud Lake, about 10 feet from dyke at various depths.
b) total tailings from processing plant.

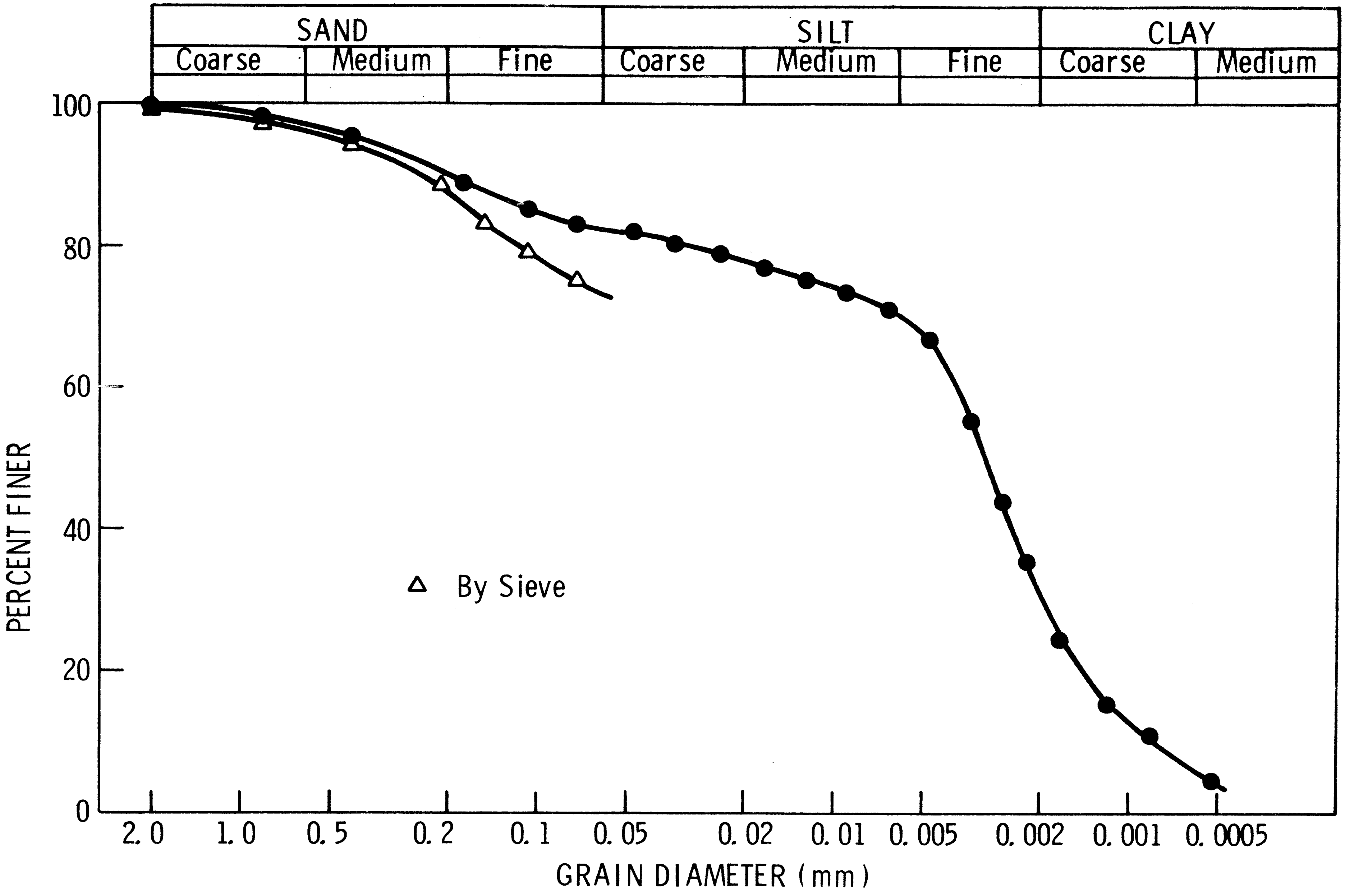


Figure 18. Grain size distribution of in-situ red muds, Mobile, Alabama.
a) #2 North Mud Lake, about 50 feet from dyke near surface
b) total tailings from processing plant

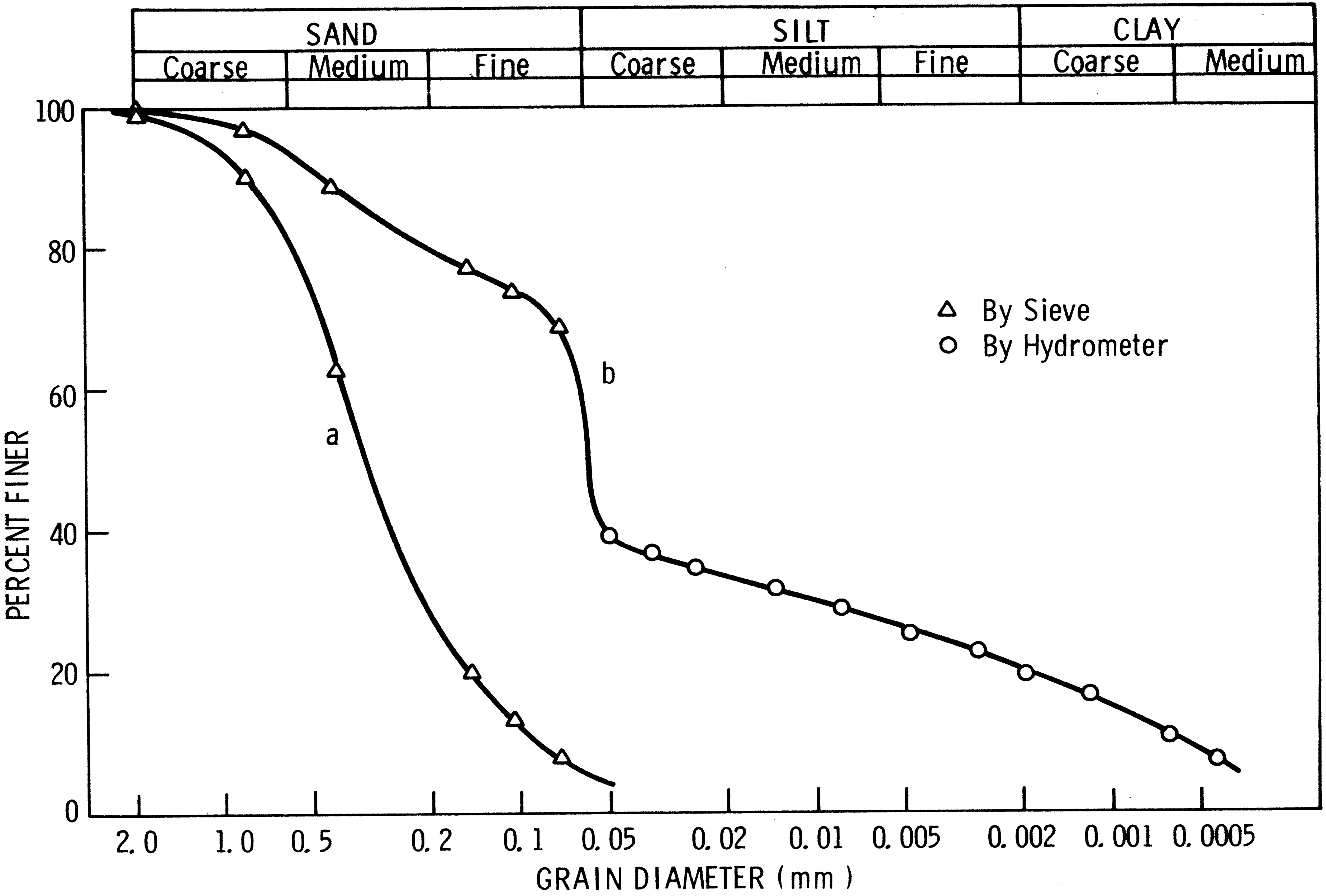


Figure 19. Grain size distribution of in-situ red muds, Point Comfort. Texas.
a) #1 Mud Lake, about 80 feet from dyke,
b) total tailings from processing plant

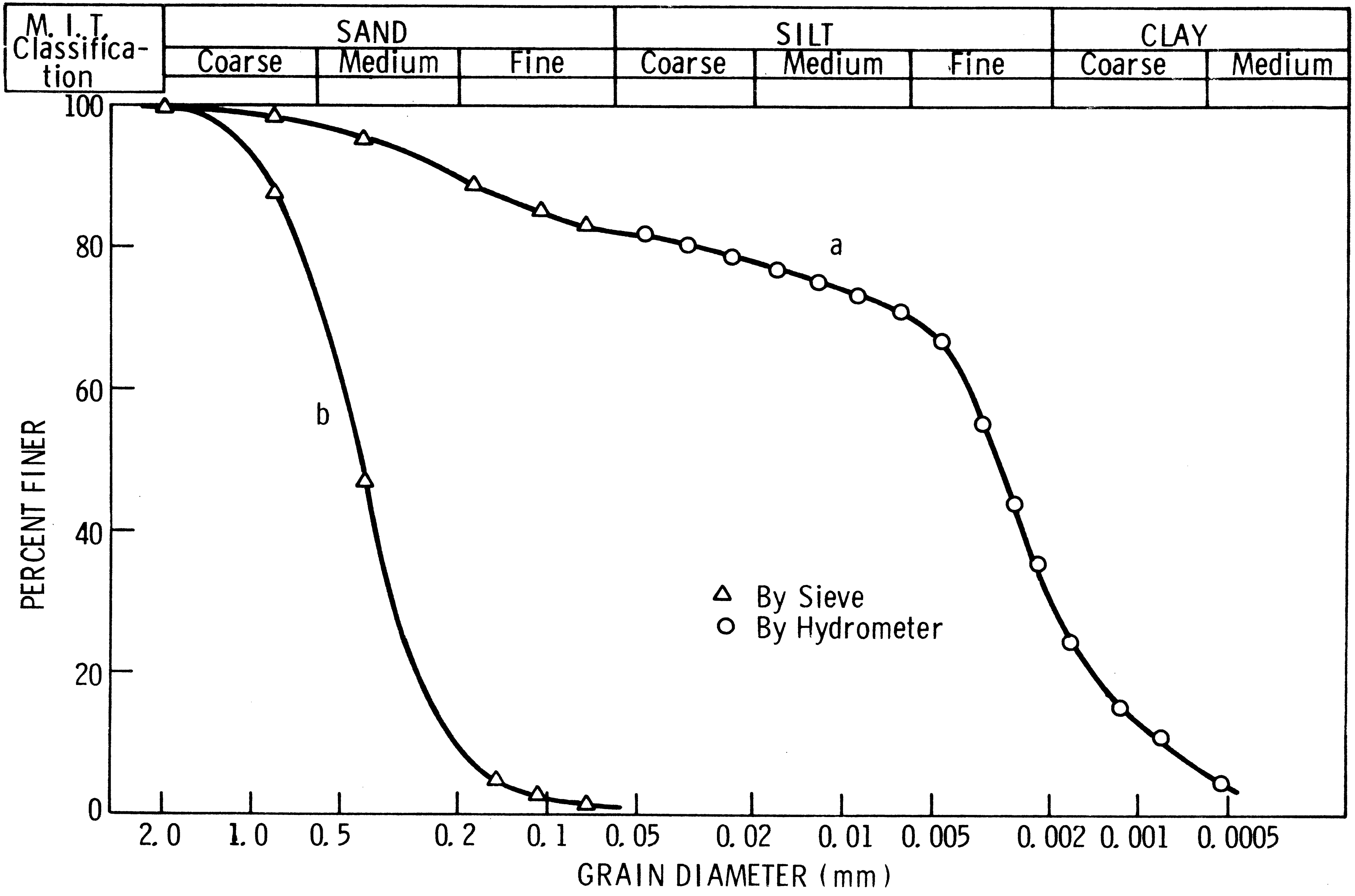


Figure 20. Grain size distribution of processing plant tailings, Mobile.
a) total tailings.
b) tailings caught in sand trap

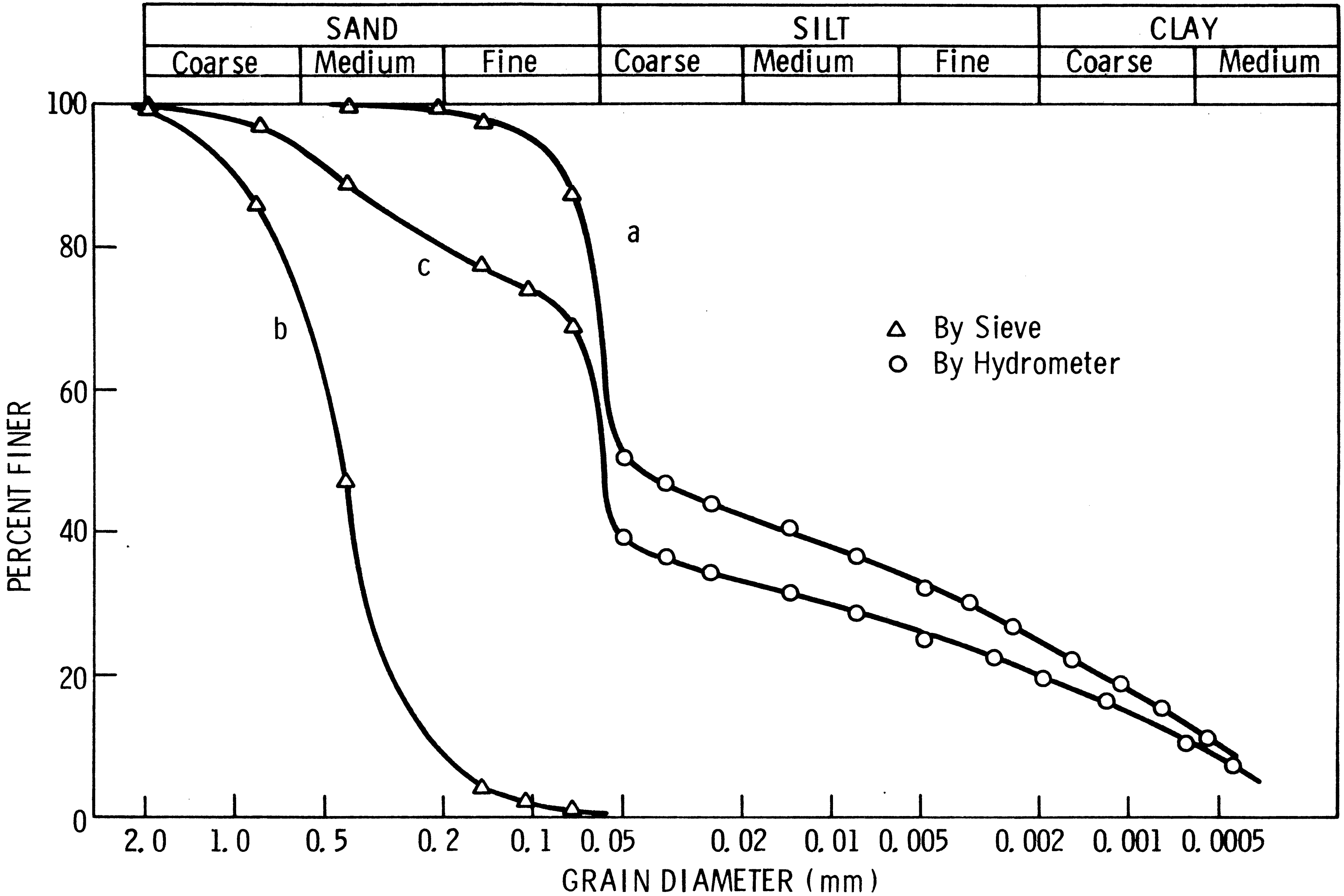


Figure 21. Grain size distribution of processing plant tailings, Point Comfort
a) from mud thickener
b) from sand
c) total tailings

TABLE 5. SUMMARY OF IN-SITU DATA, MOBILE MUD

SAMPLE LOCATION	IN-SITU WATER CONTENT (%)	PERCENT SAND*
#1 North Mud Lake ~10' from dyke		
0-1' depth	43.8	74
1-2' depth	49.1	70
2-3' depth	45.7	80
3-4' depth	37.4	87
#1 South Mud Lake ~10' from dyke		
0-30' depth	55.4	73
#2 North Mud Lake ~50' from dyke	104.3	25

*plus #200 sieve

IV. DESIGN OF EXPERIMENTAL INVESTIGATION

A. PARAMETRIC VARIATION

1. Reasons

The original research plan called for tests on in-situ samples recovered from the mud lakes. In-situ data is generally preferable particularly if the depositional environment, mode of deposition, and age of deposit influence engineering properties.

Reliance on in-situ data also has its drawbacks. The main disadvantages are unrepresentative sampling and disturbance during sampling. Both of these potential liabilities can negate the advantage cited previously. Both problems were evident in obtaining in-situ samples from the mud lakes at Mobile and Point Comfort.

Perhaps a more important limitation of working only with in-situ samples is the lost opportunity to do controlled parametric variation studies. A parametric variation study is critically important for selecting optimal mud management and dewatering strategies. In other words, if one understands how various mud properties (which are subject to control or adjustment) affect dewatering and consolidation characteristics of the muds, then the disposal facility can be designed at the point of discharge to capitalize on this information.

2. Significant Parameters

Significant parameters for a parametric variation study are those parameters which are a) known to affect engineering properties (particularly consolidation behavior) and b) capable of control or adjustment either at the plant or point of discharge. These parameters in turn can be classified according to those which are strictly mud properties (e.g., mud/sand ratio, dissolved solids, pH, initial total solids) and impoundment design parameters (e.g., drain geometry and spacing). This report is primarily concerned with the former. Section VI of the report does contain, however, a brief analysis of dewatering systems which take into account the latter parameters.

B. LABORATORY TESTING PROGRAM

1. General

Standard soil testing procedures (ASTM, 1974; Black, 1965) were followed for the most part. In recognition of the importance of dissolved solids on the engineering properties of red mud, selected samples were subjected to a leaching treatment prior to testing. Leaching consisted of washing the red muds with distilled water in a Buchner funnel until the leachate was relatively free of dissolved salt. Leaching was a slow process requiring many pore volumes throughput of distilled water. A leachate conductivity of 400 micromhos/cm was chosen as an endpoint for the leaching process. A typical leaching response curve is shown in Figure 22.

In order to examine the effect of varing the mud/sand ratios on the engineering properties of the mill tailings, samples were made up at mud/sand ratios of 5:1, 3:1, 2:1, and 100% mud on a dry weight basis. The sand came from separate shipments of sand-sized material obtained from the sand screens or traps at the Mobile and Point Comfort plants. The material defined as mud differs slightly according to plant of origin.

The Point Comfort mud came directly from the last stage thickners and includes some sand size material (i.e., plus #200 mesh size). This material was filtered at the plant and shipped to the University of Michigan in a moist condition. Supernatant saved from previous mud slurry samples was used to reconstitute some of the unleached Point Comfort samples.

The Mobile mud, on the other hand, is restricted to only minus #200 mesh size material. This mud was obtained by wet sieving the total slurry feed being discharged to the mud lakes, i.e., material coming from the mud hoppers which has sand mixed in. This slurry was shipped to the University of Michigan in 50-gallon drums. The mud (or fine grain fraction) so obtained was then centrifuged, air dried, and pulverized for future use. Supernatant from the centrifugation was likewise saved for later use in reconstituting samples for testing.

2. Compositional Analyses

Both mineralogic and chemical analyses were performed on the red muds. The chemical analyses were performed by Alcoa and the results furnished to the University of Michigan. The mineralogy is being determined by standard x-ray diffraction techniques, which only detect crystalline components.

Samples for x-ray diffraction were prepared by leaching the red mud free of dissolved salts, and then sedimenting the mud in thin

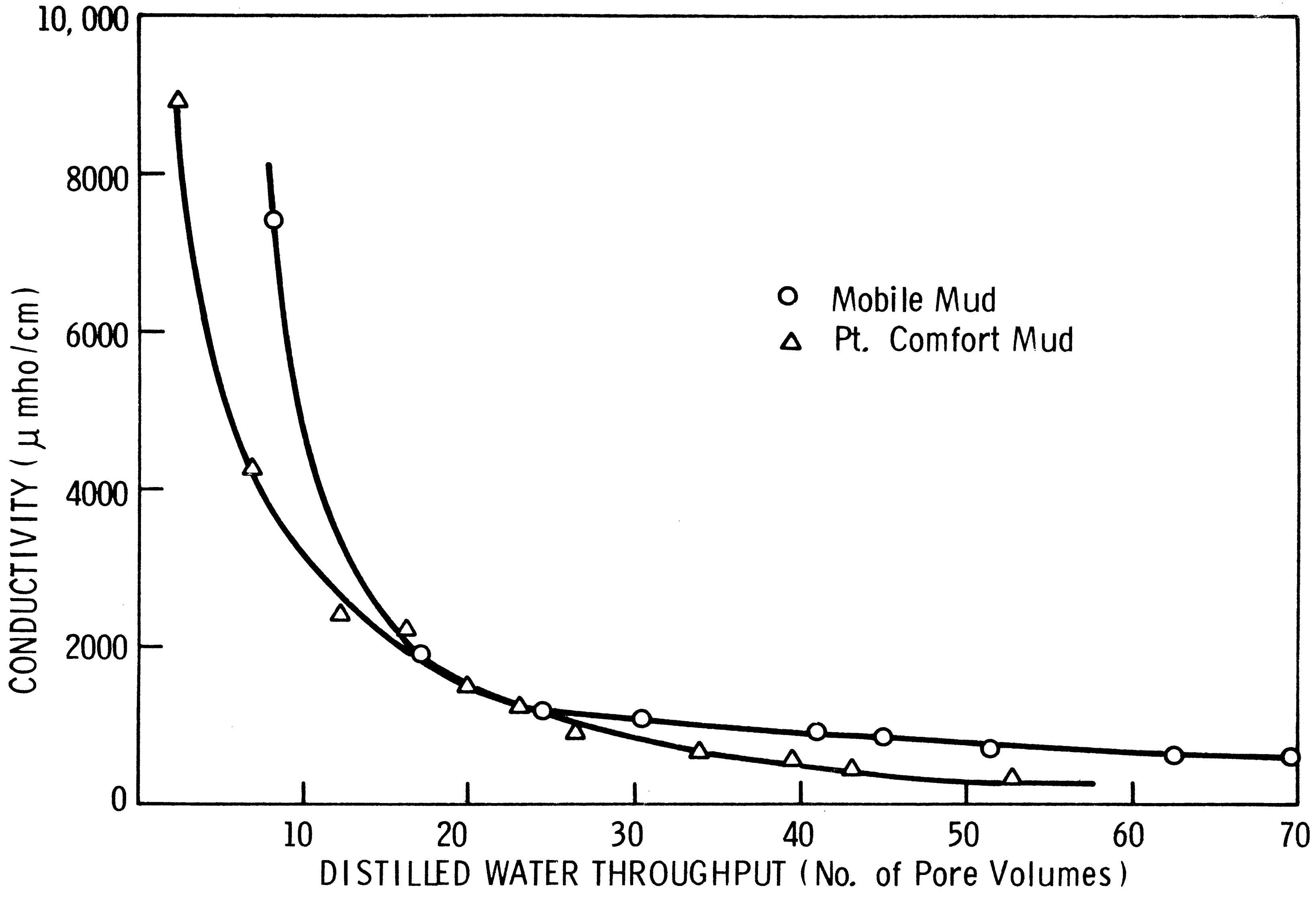


Figure 22. Leaching response of Point Comfort and Mobile red muds

layers on unglazed porcelain tiles. Two size fractions were examined, viz., minus 5- and 20 microns respectively. The samples were scanned in a Phillips Norelco x-ray diffractometer at a rate of two-theta degrees per minute. Samples were scanned in an airdry condition and also heated to 300°C and 600°C respectively prior to scanning.

3. Index Properties

The principal index properties of the red muds which are being measured include the following:

a) Atterberg limits
b) Grain size distribution (by sieving and hydrometer analysis)
c) Specific gravity of solids
d) Dissolved solids (by conductometric and gravimetric analysis)
e) Cation exchange capacity (by conductometric titration)
f) pH

The Atterberg limits have been measured on both leached (salt free) and unleached samples of red muds, on material mixed at several mud/sand ratios, and on unleached, air dry material allowed to cure for variable periods of time after mixing with either distilled water or slurry water.

The apparent grain size distribution of the red mud tailings is strongly influenced by the presence of dissolved solids and method of dispersion used during a sedimentation analysis. Accordingly the effect of leaching, pH neutralization, ultrasonic vibration and dispersant addition are being investigated in conjunction with the gradation tests.

The pH of the red muds was determined with a hydrogen ion electrode placed in both the slurry supernatant and in leached mud resuspended in distilled water at 20% solids content.

4. Consolidation Tests

The consolidation behavior of the red muds is the engineering property of greatest interest vìs a vìs the feasibility of dewatering and stabilizing impounded tailings. Specific consolidation parameters sought in this case include the compression index, coefficient of consolidation, and preconsolidation pressure. All these parameters are important in ascertaining the amount and rate of consolidation under an externally imposed load.

The consolidation testing program was designed to investigate the effects of dissolved solids, time, mud/sand ratio, stress history, and pH on the consolidation behavior of the red muds. The design of the experimental testing program is described herein; many of the tests are either in progress or yet to be completed at time of writing this report.

Samples for consolidation testing are prepared as thick slurries and poured into a slurry consolidometer at a solids content of 40 to 50 per cent. The samples are allowed to settle initially in the slurry consolidometer under the action of gravity alone. Small preconsolidation loads on the order of 1/8 to 1/4 kg/cm^2 are then applied in order to increase the solids content to the point where the samples have sufficient strength and rigidity to be trimmed and transferred to the test consolidometers.

The effect of mud/sand ratio is being investigated by performing consolidation tests on samples prepared at three mud/sand ratios. Falling head permeability tests are performed on these samples during consolidation to determine the effect of mud/sand ratio on the permeability-void ratio relationship. If possible, at least one sample at a mud/sand ratio typical of in-situ muds will be tested in a radial consolidometer in order to determine the coefficient of radial consolidation and the horizontal permeability.

The effect of stress history must be ascertained in order to formulate a suitable visco-elastic model for the consolidation process. This will be evaluated by running consolidation tests at various load increment ratios and load durations. The load increment ratio (L.I.R.) is defined as the ratio between the increment in load applied and the existing load on a sample.

In addition to the time effects observed by varying stress history, time dependent thixotropic behavior is being investigated by allowing at least one sample to remain in the slurry consolidometer for a minimum of one month prior to consolidation testing.

Finally, the pore pressure response of red muds under an externally imposed consolidation stress is being measured in some tests in order to examine the correspondence between volumetric strain and pore pressure dissipation.

The entire consolidation testing program is summarized in Table 6.

5. Shear Strenth Tests

The object of deliberate consolidation is to increase the shear strength of deposits so that the bearing capacity and stability will be adequate. Shear strength tests are being run on samples consolidated

TABLE 6. SUMMARY OF CONSOLIDATION TEST PROCEDURES

TEST NO.(1)	MUD: SAND RATIO(2)	PRETREATMENT	SAMPLE PREPARATION	BATH FLUID	L.I.R.	LOAD DURATION	ADDITIONAL MEASUREMENTS
MCON-0a	1:0	none	NORMAL	SUPERNATANT	1.0	1 da	none
MCON-0b	1:0	none	IN-RING	SUPERNATANT	1.0	1 da	none
MCON-1	1:0	none	IN-RING	SUPERNATANT	1.0	1 da	PERMEABILITY
MCON-2	5:1	none	IN-RING	SUPERNATANT	1.0	1 da	PERMEABILITY
MCON-3	3:1	none	IN-RING	SUPERNATANT	1.0	1 da	PERMEABILITY
MCON-4	1:0	none	IN-RING	CIRCULATING	1.0	1 wk	none
MCON-5	1:0	LEACHED	NORMAL	DIST. H_2O DIST. H_2O	1.0	1 da	PORE PRESSURE
MCON-6	1:0	none	IN-RING, CURED 1 mo. at 1/8Kg/cm^2	SUPERNATANT	1.0	1 da	PORE PRESSURE
MCON-7	1:0	none	NORMAL	SUPERNATANT	1.0	2 wk	none
MCON-8	1:0	none	IN-RING	SUPERNATANT	VARIABLE	1 da	PORE PRESSURE
MCON-9	1:0	NEUTRALIZE pH	IN-RING	DIST. H_2O	1.0	1 da	none
MCON-10	1:0	none	COMPACT & TRIM	SUPERNATANT	1.0	1 da	PERMEABILITY
MCON-11	1:0	none	IN-RING	SUPERNATANT	1.0	1 da	RADIAL PERM.

[1] The first letter of the test no. indicates the origin of the Red Mud (in this case, Mobile); the entire series will be repeated for Pt. Comfort, the tests being designated PCON-X.

[2] For the PCON series, a mud/sand ratio of 1:0 implies thickener mud only.

to various water contents for this purpose. Shear strenth is determined by running undrained type tests using a miniature vane shear apparatus. Both the peak and residual shear strength values are recorded with the vane apparatus. The ratio of the two provides a measure of the sensitivity of the material at any particular condition (i.e., mud/sand ratio, water content, dissolved solids content, etc.).

In addition to vane shear tests, which are relatively simple and easy to run, a few triaxial tests will be run on selected samples to determine shear strength parameters, viz., angle of internal friction and apparent cohesion.

6. Compaction-Strength Behavior

Use of the red muds as a borrow material for either a subbase or compacted structural fill requires information about compaction characteristics.

Moisture-density relationships for the red muds are being determined by compacting the mud in small molds by using impact compaction and efforts equivalent to the Modified AASHO test.

The compacted samples are extruded from their molds and tested in unconfined compression to determine how strong they are at various moulding water contents. Small amounts of lime (1-10%) will be added in later tests to examine the effect of stabilizing chemicals on the compaction-strength behavior of red mud.

V. RESULTS OF LABORATORY RESEARCH

A. COMPOSITION

1. Chemical

The results of standard chemical analyses for the Mobile and Point Comfort muds are shown in Table 7. These analyses were furnished by Alcoa. The results show that the major constituents are iron oxide (30-40%) and alumina (12-20%). Silica, titanium oxide, calcium and sodium comprised the balance. Loss-on-ignition values ranging from 11 to 20% indicate the presence of carbonates in the muds.

2. Mineralogic (Mobile)

The mineralogy of the Mobile muds was determined by x-ray diffraction. The results of the x-ray diffraction analyses are summarized in Tables 8 and 9. The crystalline constituents of the fine grained fraction of the red mud (minus 20 microns) appear to consist of hematite (Fe_2O_3) and complex aluminum silicates, silicate hydroxides, and compound carbonates. Both quartz and the clay minerals are absent. There was no evidence, for example, for the presence of kaolinite, chlorite, and hydrous mica, which are commonly found in fine grained soils. Silicon is evidently tied up in the silicate compounds cited previously.

Several of the compounds appear to be hydrated and become amorphous upon heating. A very intense diffraction peak at approximately 23 Å was present in all air dry samples examined; this peak disappeared upon heating. The hematite peak at 2.70 Å did not appear until the samples were heated. Heating also appeared to accentuate the peaks at 3.56, 3.70, and 6.50 Å. Calcite (at 3.04 Å) was absent in the minus 5 micron fraction. On the other hand, certain minerals found in the minus 5 micron fraction (@2.10, 2.21, and 2.56 Å) were missing in the minus 20 micron fraction.

B. INDEX (PHYSICO-CHEMICAL) PROPERTIES

1. Atterberg Limits

A series of Liquid and Plastic Limit tests were performed on red mud from Mobile. The tests were run on unleached and leached fine material (passing the #200 sieve), on material mixed at four different mud/sand ratios, and on unleached fine material which was

TABLE 7. CHEMICAL ANALYSIS OF RED MUDS FROM ALCOA PLANTS

SOURCE AND TYPE OF RESIDUAL	COMPOSITION - per cent by weight						
	SiO_2	Fe_2O_3	Al_2O_3	CaO	Na_2O	TiO_3	L.O.I.
Point Comfort sand classifier	6.2	37.5	12.6	15.2	1.5	1.4	20.0
Point Comfort thickener mud	8.5	41.6	16.3	6.7	6.8	5.5	11.3
Mobile total tails	14.4	30.1	20.7	6.1	6.6	9.3	12.0

TABLE 8. X-RAY DIFFRACTION DATA, MOBILE RED MUD

SIZE FRACTION	SAMPLE TREATMENT								
	AIR DRY			HEAT TO 300°C			HEAT TO 600°C		
	d (Å)	i	I	d (Å)	i	I	d (Å)	i	I
MINUS 5 MICRONS	2.10	13	77	2.09	10	53	2.09	11	48
	2.22	8	47	2.21	8	42	2.21	9	39
	2.58	17	100	2.56	17	90	2.56	19	83
	2.70	ABSENT		2.70	8	42	2.70	17	74
	3.04	ABSENT		3.04	ABSENT		3.04	ABSENT	
	3.56	11	65	3.56	19	100	3.53	21	92
	3.71	12	70	3.72	16	84	3.70	21	92
	4.19	8	47	4.17	13	68	4.19	ABSENT	
	6.51	8	47	6.50	16	84	6.49	23	100
	23.2	OFF SCALE		23.2	ABSENT		23.2	ABSENT	
	AIR DRY			GLYCOLATED					
MINUS 20 MICRONS	2.10	ABSENT		2.10	ABSENT				
	2.22	ABSENT		2.22	ABSENT				
	2.58	ABSENT		2.58	ABSENT				
	2.70	ABSENT		2.70	ABSENT				
	3.04	8	42	3.04	8	42			
	3.56	17	90	3.56	18	95			
	3.70	19	100	3.70	19	100			
	4.20	10	53	4.19	10	53			
	6.50	9	47	6.40	9	47			
	23.2	OFF SCALE		23.2	ABSENT				

TABLE 9. ANALYSIS OF X-RAY DIFFRACTION DATA, MOBILE RED MUD

d-spacing (Å)	Comments	Possible minerals[1]
2.10	Absent in 20 micron fraction	?
2.21	" " " " "	?
2.56	" " " " "	iron silicate hydroxide $Fe_3Si_2O_5(OH)_4$ calcium sodium carbonate $Na_2Ca_2(CO_3)_3$
2.70	Absent in air dry samples	hematite Fe_2O_3 , goethite FeO(OH)
3.04	Absent in 5 micron fraction	calcite $CaCO_3$
3.56	Intensity increases with incr. heating & particle size	iron silicate hydroxide $Fe_3Si_2O_5(OH)_4$ calcium silicate hydrate $CaSi_2O_5 \cdot 2H_2O$
3.70	" " "	aluminum carbonate silicate $3NaAPSiO_4 \cdot Na_2CO_3$
4.19	Absent in sample heated to 600°C	goethite FeO(OH) , sodium aluminum silicate hydrate $Na_2(Al_2Si_3O_{10}) \cdot 2H_2O$
6.50	Intensity incr. w/ incr. heating	sodium aluminum silicate hydrate $Na_2(Al_2Si_3O_{10}) \cdot 2H_2O$
23.0	V. strong peak, disappears upon heating	calcium silicate hydrate $CaSi_2O_5 \cdot 2H_2O$

---

(1) Based on "Inorganic Index to the Powder Diffraction File," published by Joint Committee on Powder Diffraction Standards, 1971

allowed to cure for variable time periods prior to testing. For Point Comfort, only one set of Atterberg limits tests was run on the unleached thickener mud. All Liquid and Plastic Limit tests were performed according to the test procedure described in ASTM D423-66 and D425-69, respectively. The results are presented in Figure 23 and Table 10.

The results in Figure 23 show that an essentially linear relationship exists between the Atterberg limits and sand content. This is in agreement with the findings of Skempton (1953) and Paduana (1966), who express this relationship in terms of Plasticity Index (LL-PL) vs. clay content.

The results of Table 10 indicate a marked decrease in the plasticity of Mobile mud upon leaching.*

The unleached Point Comfort thickener mud is much more plastic than the unleached Mobile mud. According to Casagrande's (1948) Plasticity Chart, the plasticity of both Red Muds is similar to that of an inorganic silt or clayey silt.

It should be noted that the plasticity varied with curing time. Unleached Mobile mud tested two hours after mixing, had a Liquid Limit of 49 and Plastic Limit of 40. However, the samples tested at two days and six days, and presumably at any time thereafter, had limits of 46 and 39, as shown in Table 10.

2. Grain Size Distribution

Grain size analysis of Mobile and Point Comfort Red Muds was performed using the procedure described in ASTM D422-63, with exceptions as noted below.

In performing the sieve analysis on all samples, material retained on the #200 sieve was washed through that sieve in order to accurately determine the percent of material passing the #200 sieve. In the case of samples containing an appreciable amount of fines, the larger sieves were also found to clog; therefore, the material was washed through the entire stack of sieves.

The effects of both leaching and concentration of dispersing agent on apparent grain size distribution were investigated using

---

*Quite a bit of difficulty was encountered in performing the Atterberg Limits tests on the leached fine material. The sample exhibited a high degree of sensitivity, requiring many trials before consistent results were obtained.

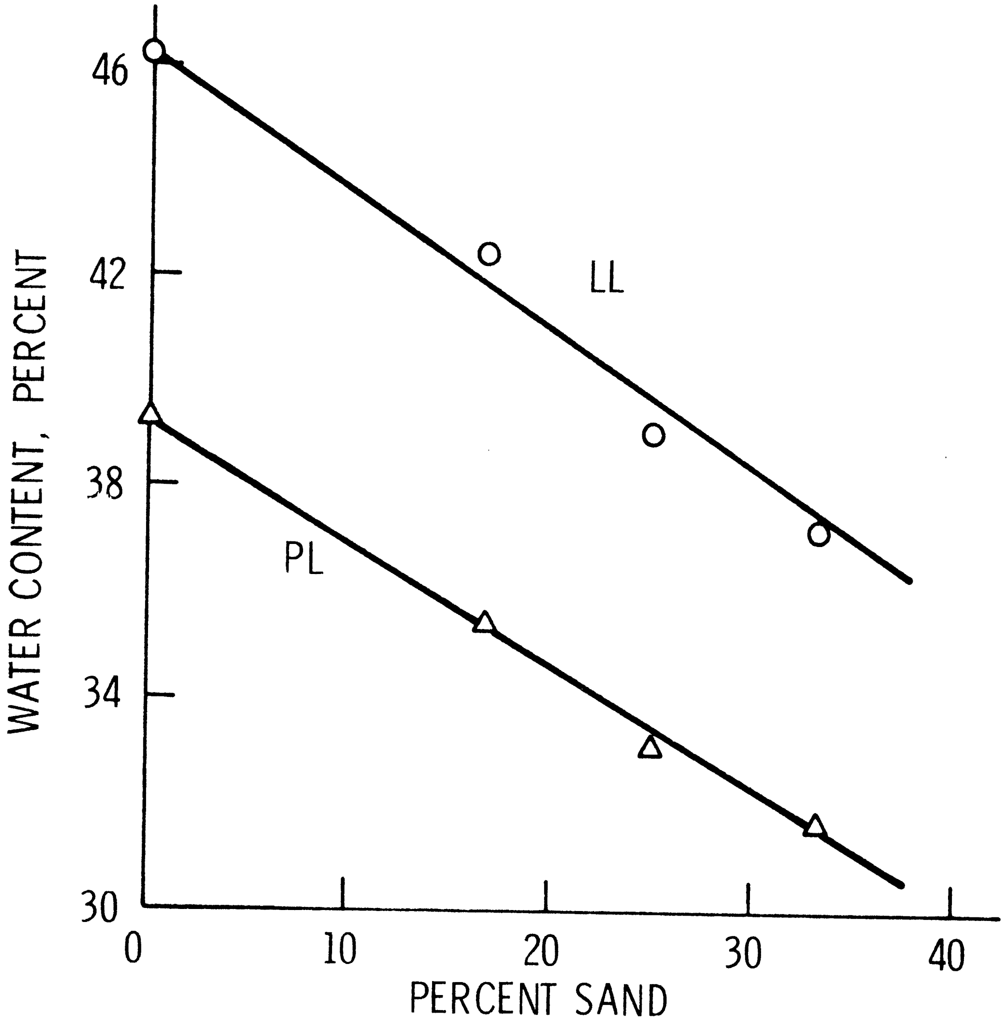


Figure 23. Influence of sand content on the Atterberg limits of Mobile mud.

TABLE 10. ATTERBERG LIMITS OF ALCOA RED MUDS

MATERIAL	LIQUID LIMIT L.L.	PLASTIC LIMIT P.L.	PLASTICITY INDEX P.I.
MOBILE unleached mud	46	33	7
" leached mud	41	37	4
POINT COMFORT unleached thickener mud	46	33	13

Notes:
- Mobile samples cured 6 days
- Point Comfort samples cured 2 days
- unleached samples mixed with slurry water
- leached samples mixed with distilled water

TABLE 11. SUMMARY OF INDEX PROPERTIES OF ALCOA RED MUDS

Property	Mobile	Point Comfort
1. % fines (minus #200 sieve)	83%	69%
2. Specific Gravity		
- of mud	2.84	3.45
- of sand	3.16	
3. Dissolved Solids, %	4.5	3.8
4. pH - of leached mud*	10.3	9.6
- of slurry water	13.0	13.2
5. Cation Exchange Capacity, $\frac{\text{meq}}{\text{100gms}}$	5.2	-

*resuspended in distilled water to 20% solids by weight the fine fraction of Mobile red mud. Hydrometer tests were conducted on both unleached and leached (salt free) mud. Dispersion of the mud was aided by the standard ASTM procedure of adding 125 ml of 4% calgon solution. Tests were also performed on totally leached samples, using twice the recommended amount of dispersing agent. The results of this study are presented in Figure 24.

The grain size distribution of the totally leached material dispersed by the standard amount of dispersing agent, curve (a), can be seen to exhibit the lowest degree of flocculation. Doubling the amount of dispersing agent yields results very similar to those due to incomplete leaching. The results indicate that the suspension obtained by adding twice the recommended amount of dispersing agent is not a stable one. After two months, a high degree of flocculation and particle aggragation is apparent as shown by curve (d).

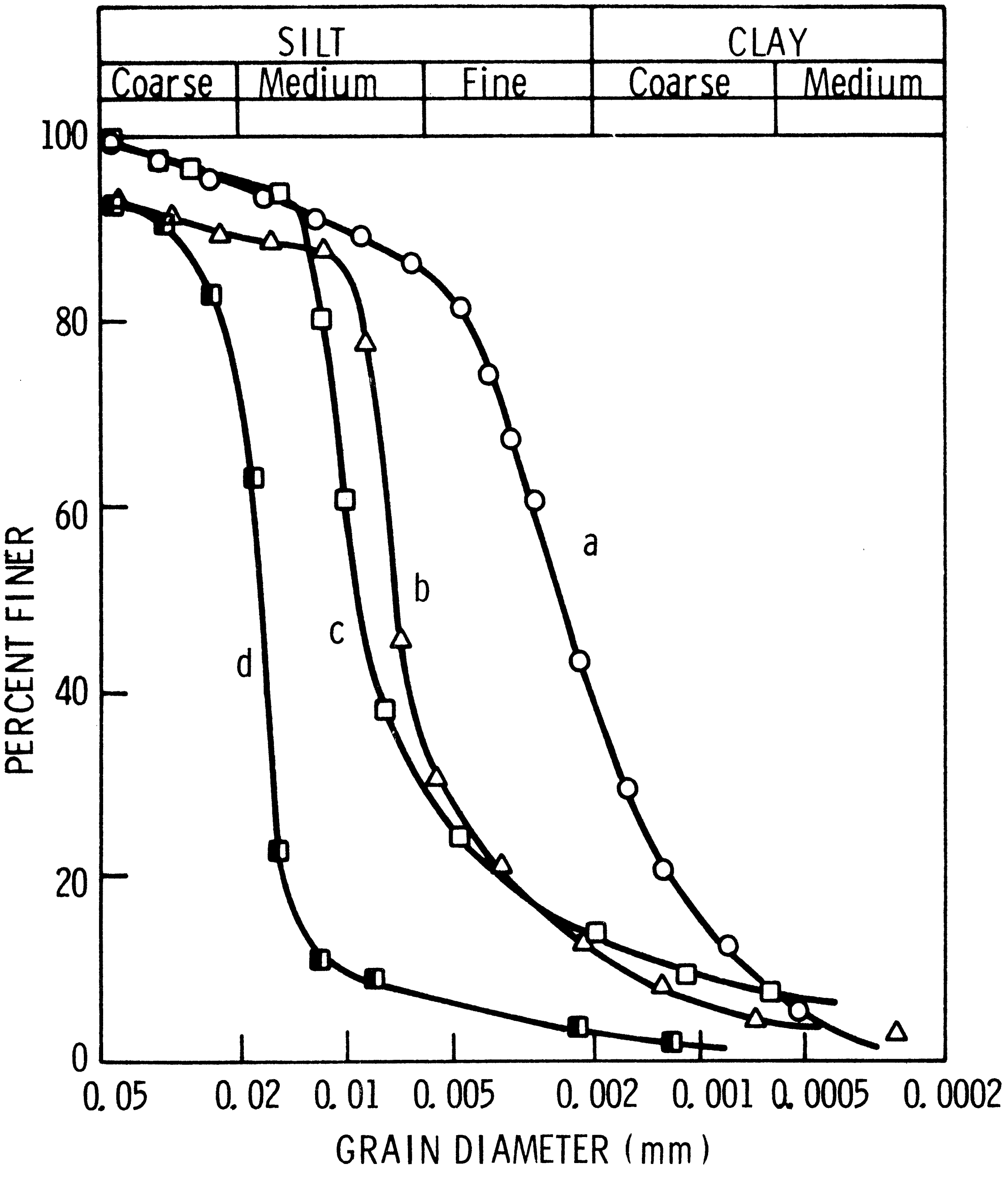
The composite grain size distribution of total tailings from both the Mobile and Point Comfort processing plants were computed by weighting the component curves with the proper mud/sand ratio. The 'as-received' mud/sand ratio was 4.7/1.0 for the Mobile tailings, whereas 3.6/1.0 was reported for the Point Comfort tailings. The composite grain size distributions were shown previously in Figures 20 and 21 (Sec. III). Note that the Mobile Red Mud contains 30% clay-sized particles, and the Point Comfort Red Mud contains 20%.

Based on Grain Size Distribution and Atterberg Limits, both Red Muds would be classified as ML (i.e., non-plastic, sandy, clayey silts) according to the Unified Soil Classification System.

3. Specific Gravity

All specific gravity determinations were performed according to ASTM D 854-58. The only difficulty encountered in performing this test was the complete removal of air after mixing in a high-speed mixer. Air removal was finally accomplished by means of vacuum applied for a period of three hours.

Since the presence of salts affects the specific gravity, tests were performed on leached samples. The specific gravity of leached fine Mobile material was determined to be 2.84. Two tests were performed on both the sand fraction of the Mobile mud and the leached thickener mud from Point Comfort. The average specific gravity of the Mobile sand was 3.16; of the Point Comfort mud, 3.45. The specific gravity of the Point Comfort coarse material is yet to be



a) completely leached, dispersed with 125 ml 4% Calgon
b) partially leached, dispersed with 125 ml 4% Calgon
c) completely leached, dispersed with 250 ml 4% Calgon
d) same as (c) but sample allowed to stand for 2 mos. after mixed with dispersant

Figure 24. Grain size distribution of Mobile mud (minus #200 sieve) showing effect of leaching and dispersing agent concentration

determined. Specific gravity test results are summarized in Table 11.

4. Dissolved Solids

The dissolved solids content of both the Mobile and Point Comfort supernatant fluid was determined gravimetrically by oven drying a known weight of supernatant, and weighing the residual salts. As indicated in Table 11, the dissolved solids contents of the Mobile and Point Comfort material are 4.5% and 3.8%, respectively. These values agree quite well with those obtained by measuring the conductivity of the supernatant. The conductivity, however, is most accurate in determining dissolved solids concentration in meq/liter; the conversion to ppm is not an exact one because of the unknown valence of all ions in solution.

5. Hydrogen Ion Activity

The pH of Mobile and Point Comfort supernatant fluid and suspensions containing 20% leached fine material was measured using a Corning pH meter. The pH of Mobile and Point Comfort supernatant is 13.0 and 13.2, respectively; of the suspended leached mud, 10.3 and 9.6, respectively. These values indicate the extreme alkalinity of Red Muds.

6. Cation Exchange Capacity

The cation exchange capacity of Mobile mud was determined by conductometric titration. The exchange capacity was 5.2 milliequivalents per 100 gms. This is a relatively low value, comparable to that of kaolinite which is commonly regarded as low activity clay with little exchange capacity.

The results of all index properties and physico-chemical tests are summarized in Table 11.

C. CONSOLIDATION TESTS

All consolidation tests were performed using the procedure described in ASTM D2435-70, with modifications as noted previously and in the text which follows. Sample identification and consolidation testing procedures were summarized earlier in Table 6, Section III. To date, tests MCON-Oa, MCON-Ob, MCON3, MCON5, MCON 6, and PCON7 have been completed.

The equipment available for performing consolidation tests includes one Anteus and three Karol-Warner Consolidometers. The Anteus Consolidometer is the more versatile instrument; unfortunately it also contains aluminum parts which are rapidly corroded by unleached Red Mud. Therefore, only leached samples could be tested in this unit. The Karol-Warner Consolidometers can be equipped with either floating or fixed rings. Using the floating ring only two-way drainage is possible, thereby disallowing the measurement of permeability or pore pressure. With the fixed ring, one-way drainage can be imposed, and either permeability or pore pressure can be measured.

The greatest difficulty in performing the consolidation tests was sample preparation. The requisites for good samples included full saturation, relative homogeneity, repeatibility, and sufficient strength to enable handling. The following schemes were developed to meet these requirements.

For tests on samples with mud/sand ratios of 1:0, the air-dry material (either unleached or leached free of dissolved solids) was mixed at a moisture content which would allow pouring, but minimize particle size segregation during sedimentation. This moisture content varied between 100% and 150% (50% to 40% solids by weight), depending on the origin of the material and the dissolved solids content. The resulting slurry was then de-aired under vacuum and transferred to a 4" diameter slurry consolidometer. The slurry samples were preloaded here to a sufficiently high pressure to reduce the moisture content to a point where the samples were coherent enough to allow trimming into a 2.5" consolidation ring. The required load varied between 0.125 and 0.25 kg/cm^2; the resulting moisture content varied from 50% to 60% (67% to 60% solids by weight), depending on amount of dissolved salts and sand. This scheme is referred to as 'normal' sample preparation in Table 6. Test MCON-Oa was performed using this method.

In order to minimize sample disturbance due to trimming into the consolidation ring, a further modification was investigated. The consolidation ring, seated on a mating 1.5" high spacer ring, was placed inside the slurry consolidometer prior to the introduction of the slurry. Using this method, referred to as 'in-ring' sample preparation, not only was the amount of trimming minimized, but all samples were taken from precisely the same location. Test MCON-Ob was performed using this technique. The results showed a dramatic reduction in sample disturbance, indicated by the sharp break in the void ratio-log pressure curve at the preconsolidation pressure, as opposed to the smooth void ratio-log pressure curve exhibited by MCON-Oa. The 'in-ring' technique, therefore, was used whenever possible.

For tests on samples containing sand, a slight variation of the 'in-ring' technique was employed. The air-dry material (mixed at the desired mud/sand ratio) was introduced into the slurry consolidometer containing the consolidation ring, and allowed to imbibe fluid from the base. After the fluid level was above the slurry level, vacuum was applied for one day. Using this technique, no settling of sand was permitted, thus insuring a relatively homogeneous sample (i.e., no particle size segregation).

The effect of preconsolidation load duration in the slurry consolidometer is illustrated in Figure 25. Although the compression index (defined as the slope of the linear portion of the void ratio-log pressure curve) for the two tests cited are almost identical, as presented in Table 12, the apparent preconsolidation pressure exhibited by MCON6 is almost four times the actual preconsolidation pressure. The coefficient of consolidation is also one order-of-magnitude higher, and the computed permeability is 2 to 4 times higher for MCON-6.

The phenomenon of apparent overconsolidation may be caused by interparticle cementation which is related to the high dissolved solids content of the red mud. This overconsolidation phenomenon has been observed by Kenney, Moum & Berre (1967) in iron-rich, sensitive, saline soils. This finding may be extremely significant in the design of dewatering schemes for mud lakes, as will be discussed later. The time related effects of 'apparent overconsolidation' require further investigation.

The effect of mud/sand ratio on consolidation behavior is depicted in Figure 26. The sample containing 25% sand settled to a lower void ratio in the slurry consolidometer than did the pure mud at the same pressure; moreover, its compressibility is 33% lower than that of the pure mud. In addition, its computed permeability is nearly the same as that of the pure mud, and its coefficient of consolidation is 2-3 times higher than that of pure mud. The

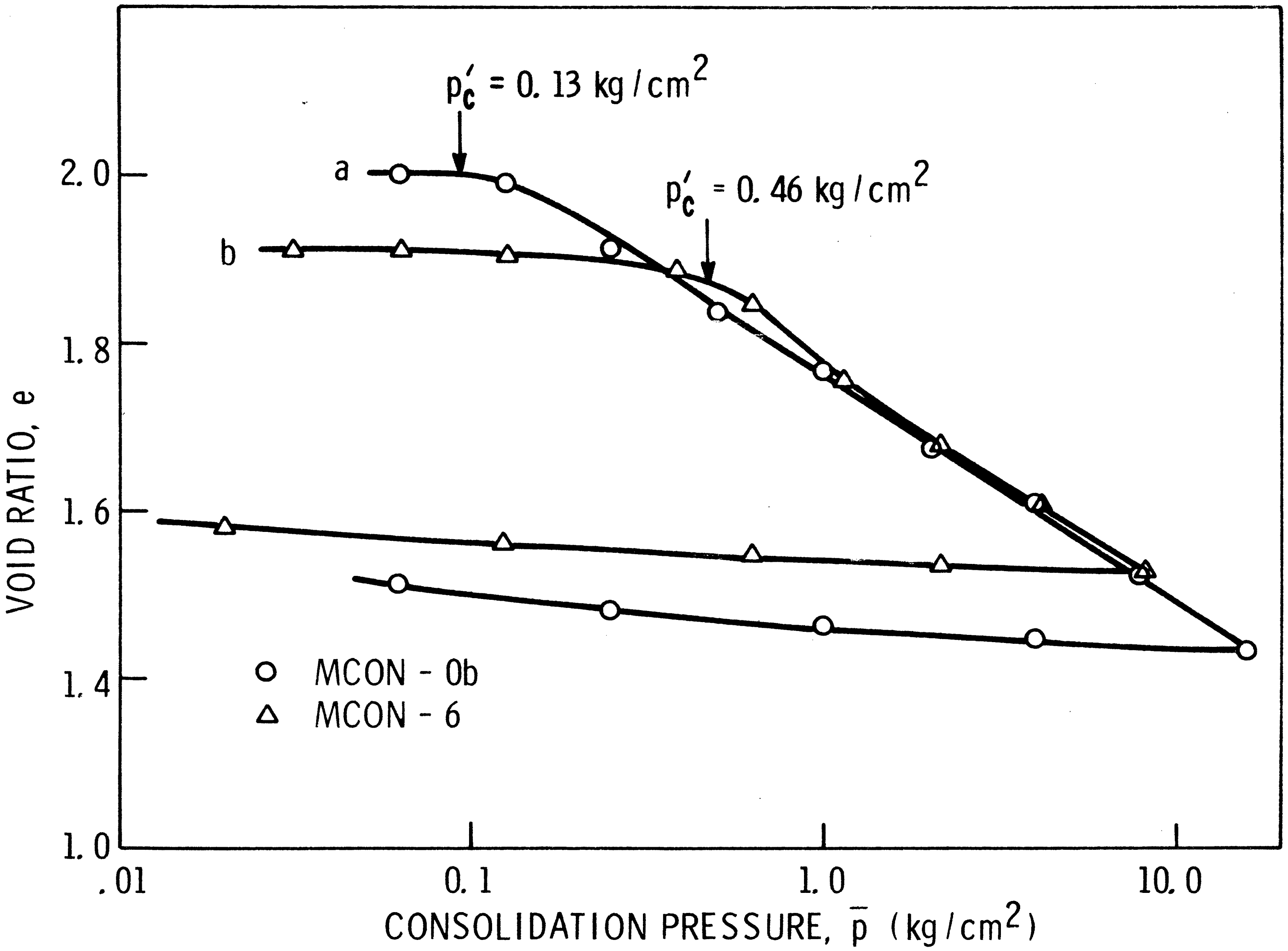


Figure 25. Void ratio-pressure curves for unleached Mobile mud showing effect of preconsolidation load duration
a) 2-day preconsolidation time
b) 32 day preconsolidation time

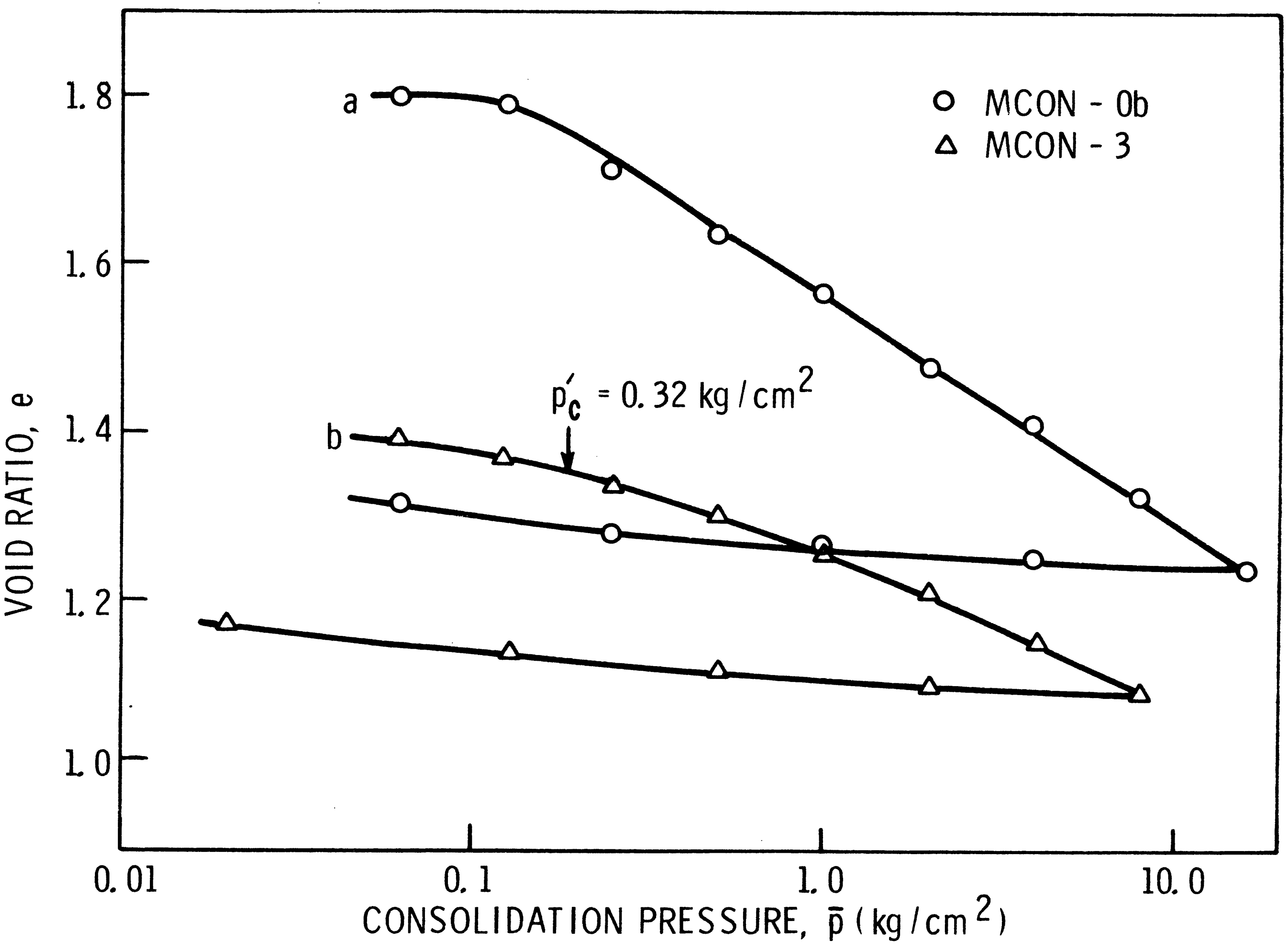


Figure 26. Void ratio-pressure curves for unleached Mobile muds
a) mud only
b) mud/sand ratio of 3:1

latter fact indicates that if Red Mud slurry is pumped to lakes at a mud/sand ratio of 3:1, the time necessary to attain any desired degree of primary consolidation could be as little as one-third the time necessary for the same depth of pure mud to reach the same degree of consolidation.

The effect of dissolved solids content on sonsolidation behavior is shown in Figure 27. Although it is difficult to determine the apparent preconsolidation pressure of the leached material due to sample disturbance, its compressibility is less than 50% that of unleached material. Also, its coefficient of consolidation is one order-of-magnitude lower than that of unleached material.

A comparison of the consolidation behavior of unleached Mobile material passing the #200 sieve and Point Comfort thickener mud (containing 12% sand) is presented in Figure 28. Although the compressibility of the Point Comfort mud is about 30% higher than that of the Mobile mud, its coefficient of consolidation is one order-of-magnitude lower than that of Mobile mud, and one order-of-magnitude lower than the 3:1 mud/sand Mobile mud. Furthermore, the Point Comfort thickener mud appears to be 4 to 5 times less permeable than either pure or 3:1 mud/sand Mobile mud.

The relationships between permeability (as measured during consolidation) vs. consolidation pressure, and permeability vs. void ratio are illustrated in Figures 29 and 30. All of the consolidation test results are summarized in Table 12.

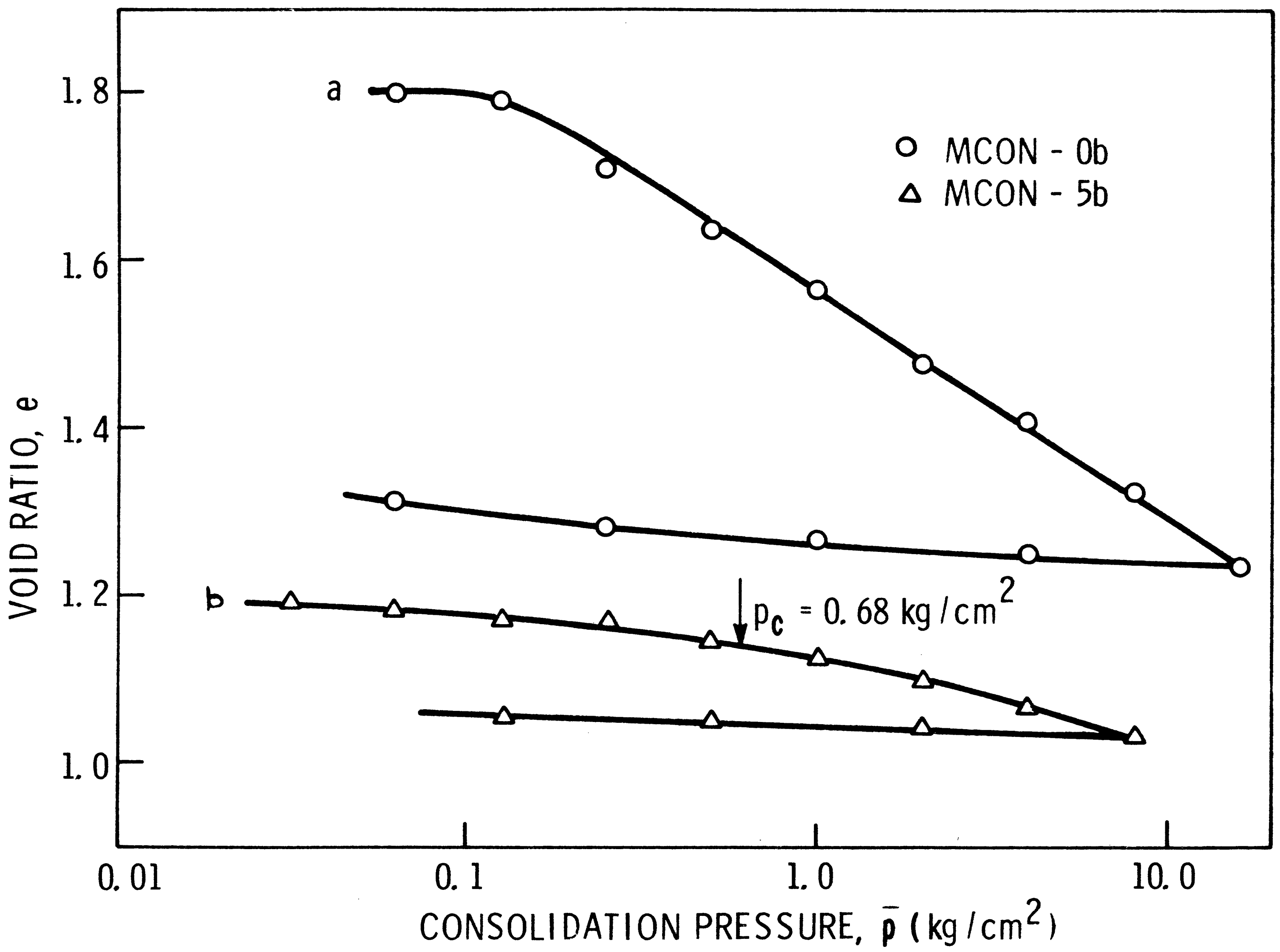


Figure 27. Void ratio-pressure curves for Mobile mud showing effect of dissolved solids content
a) unleached
b) leached (salt free)

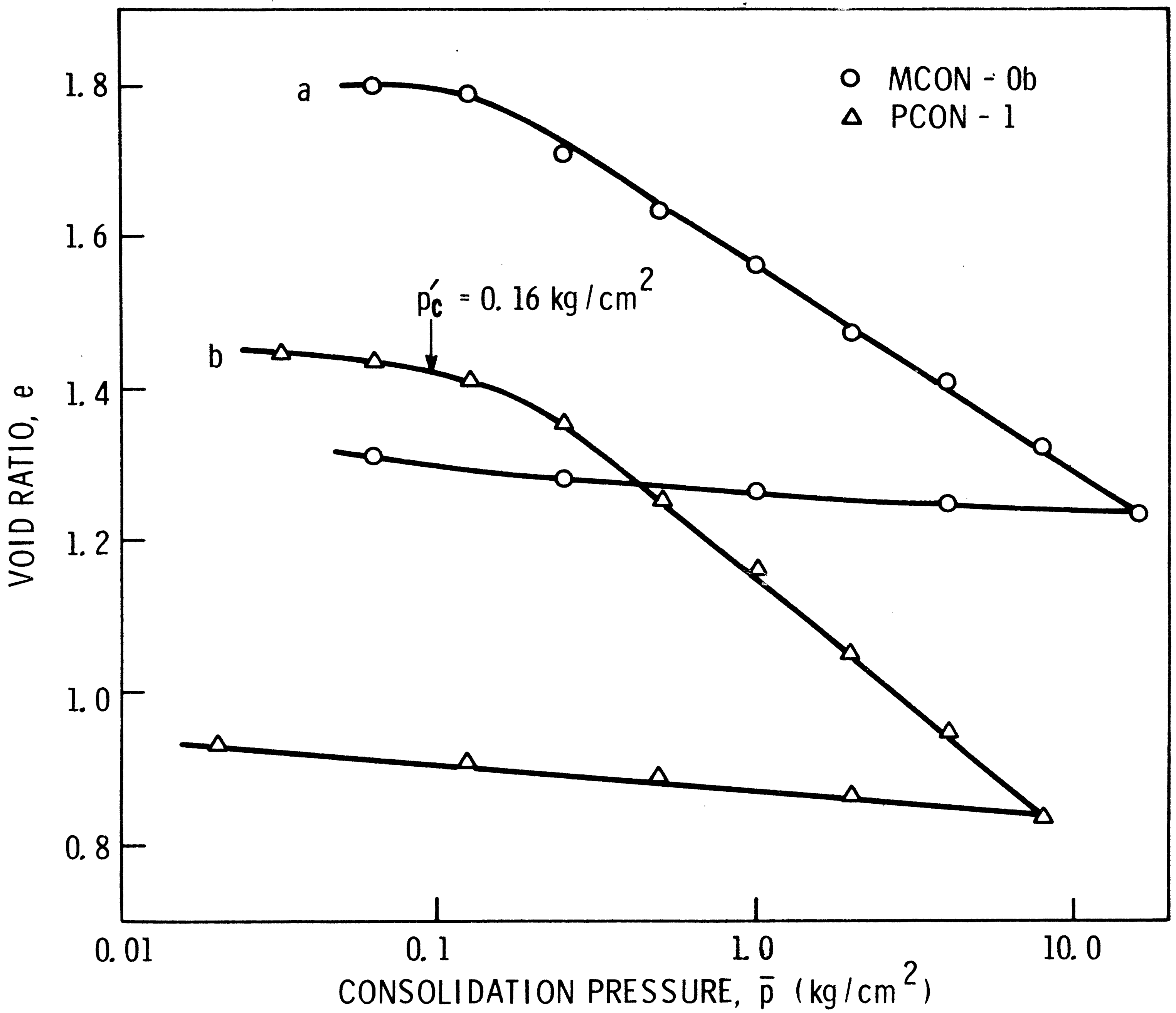


Figure 28. Void ratio-pressure curve comparison between Mobile (MCON-0b) and Point Comfort (PCON-1) muds

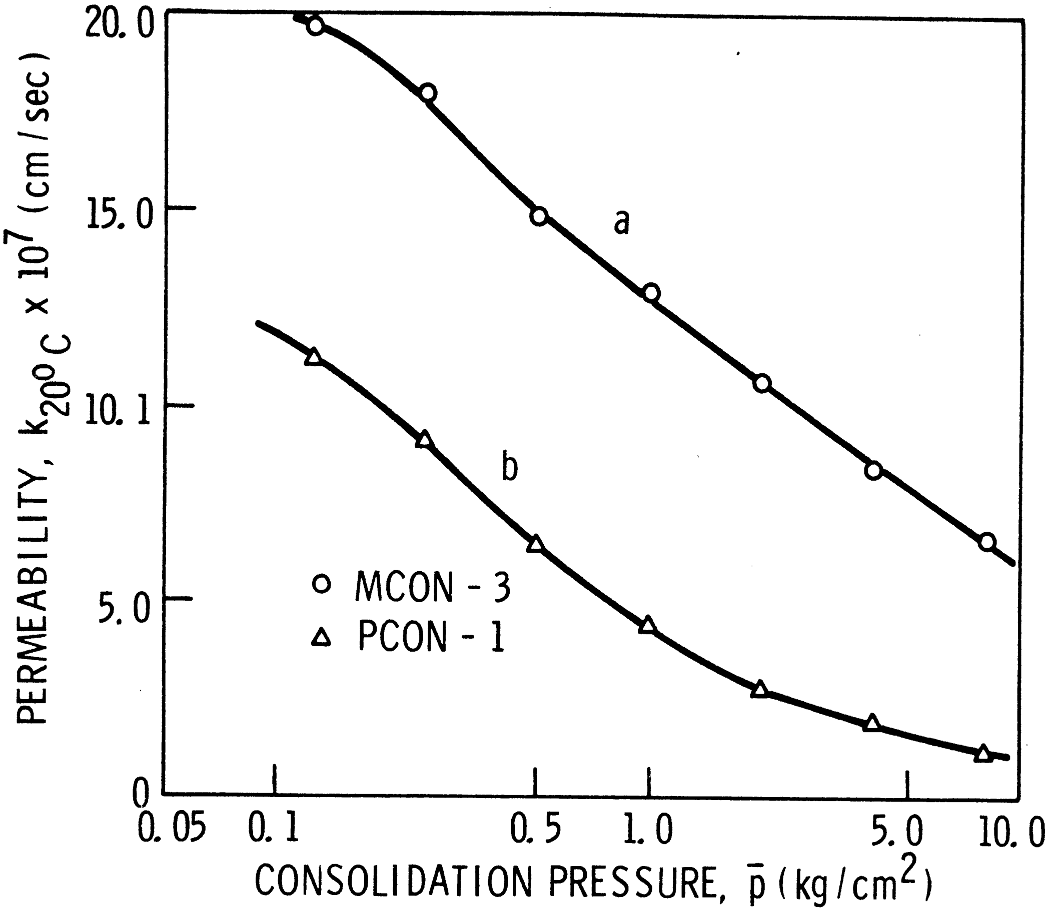


Figure 29. Permeability measured during consolidation of unleached mud samples

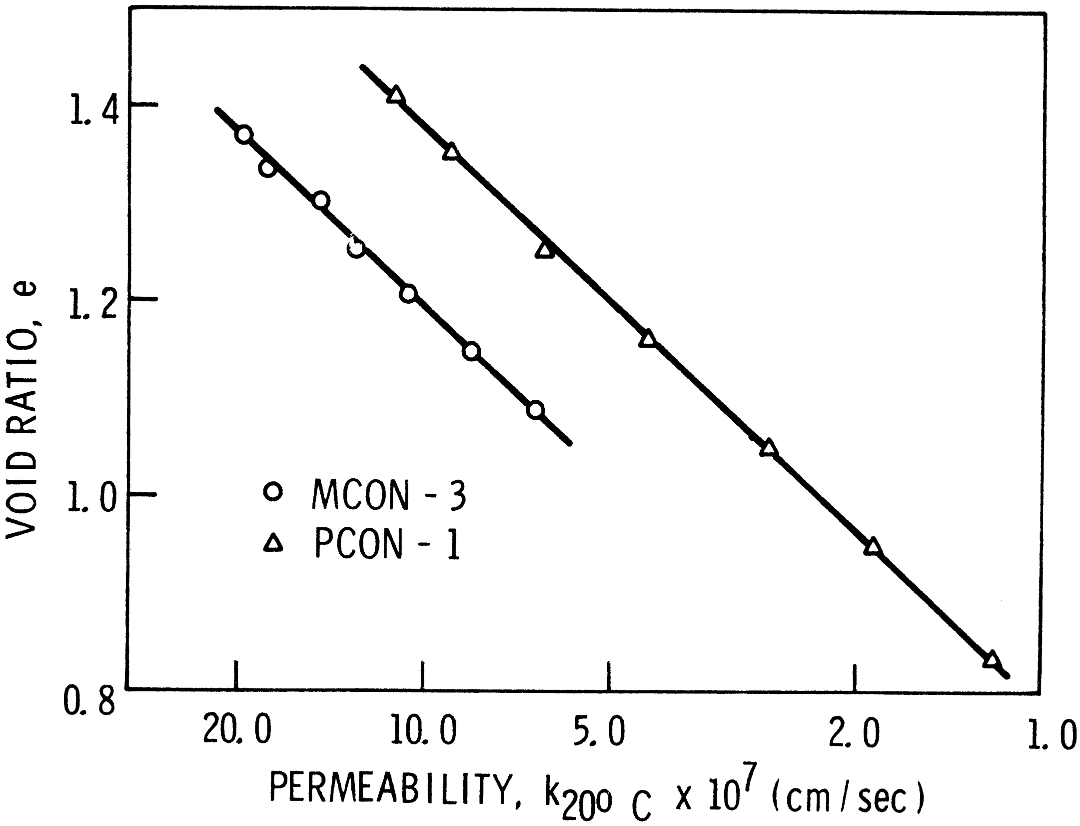


Figure 30. Permeability vs. void ratio relationship during consolidation

TABLE 12. SUMMARY OF CONSOLIDATION TEST RESULTS

TEST NO.	TEST DESCRIPTION	ACTUAL PRECONSOL. PRESSURE, Pc (Kg/cm^2)	APPARENT PRECONSOL. PRESSURE, Pc (Kg/cm^2)	COMPRESSION INDEX Cc	COEFF. OF CONSOL. c_v (cm^2/sec)	MEASURED PERMEAB. $K_{20^\circ C}$ (cm/sec) X10^6	COMPUTED PERMEABILITY K' (cm/sec) X10^6
MCON-Ob	unleached Mobile mud	0.125	0.13	0.27	.003-.03	-	0.2-2
MCON-6	preconsol. to 1/8 Kg/cm^2 for 32 da	0.125	0.46	0.26	0.06-0.14	-	0.9-4.9
MCON-3	3:1 mud:sand	0.125	0.32	0.18	0.009-0.05	0.7-2.0	0.2-1.8
MCON-5b	leached Mobile mud	-	0.68	0.12	2.91×10^{-4} -2.7×10^{-2}		
PCON-1	unleached Point Comfort thickener mud	0.188	0.16	0.34	7.5×10^{-4} -3.7×10^{-3}	0.1-1.1	0.05-0.4

D. VANE SHEAR TESTS

Miniature, laboratory vane shear tests were performed on all consolidation samples, before and after consolidation, using a Wykeham-Farrance Laboratory Vane Apparatus. The results are presented in Table 13. Most of the values shown are averages of several measurements.

As can be seen, all samples are quite weak prior to consolidation. Although the 3:1 mud/sand sample has a significantly lower equilibrium moisture content at the same consolidation pressure than the mud alone, the strengths are nevertheless similar. The 3:1 mud/sand sample appears to be more sensitive.

The leached sample also exhibited a lower water content than the unleached material at the same consolidation pressure. The strength of the leached sample, however, is about 30% higher than that of the unleached sample. The sensitivity of the consolidated leached material is very high; its value is strongly dependent on the strain rate during testing.

The unleached Point Comfort thickener mud dewaters to a lower moisture content (higher % solids) than the unleached Mobile mud at the same pressure. The strength of the consolidated Point Comfort thickener mud is three times as great as that of the Mobile mud, and their sensitivities are similar. The sensitivity of the consolidated, unleached Point Comfort thickener mud is also quite strain-rate dependent.

It should be noted that the values of shear strength, as determined in this work, are approximately 4 times lower than those reported by Jenny (1973). The values of sensitivity, however, are in quite close agreement.

E. COMPACTION-STRENGTH BEHAVIOR

Compaction tests were performed on unleached Mobile material having a mud/sand ratio of 3:1. The compaction was performed in a Harvard miniature mold using an impact hammer designed to impart a compactive effort per volume of material equivalent to the modified AASHO Test. After compaction at various water contents the samples were extruded from the mold and subjected to unconfined compression tests. The results are presented in Figure 31.

TABLE 13. VANE SHEAR TEST RESULTS

MATERIAL	MAXIMUM CONSOLIDATION PRESSURE(Kg/cm^2)	w/c (%)	SHEAR STRENGTH s (Kg/cm^2)	SENSITIVITY S_t
unleached Mobile mud (#200 sieve)	1/8 1/4 8 16	62.3 59.2 50.5 48.9	0.04 0.07 0.64 0.72	4.4 5.5 6.5 6.6
unleached Mobile mud (mud:sand=3:1)	1/8	51.9	0.04	6.0
leached Mobile mud (#200 sieve)	- 8	48.7 40.78	0 0.82	- 6.5-41*
unleached Point Comfort thickener mud	3/16 8	54.3 40.7	0.07 1.98	5.8 4.8-12

*residual strenth very strain-rate dependent

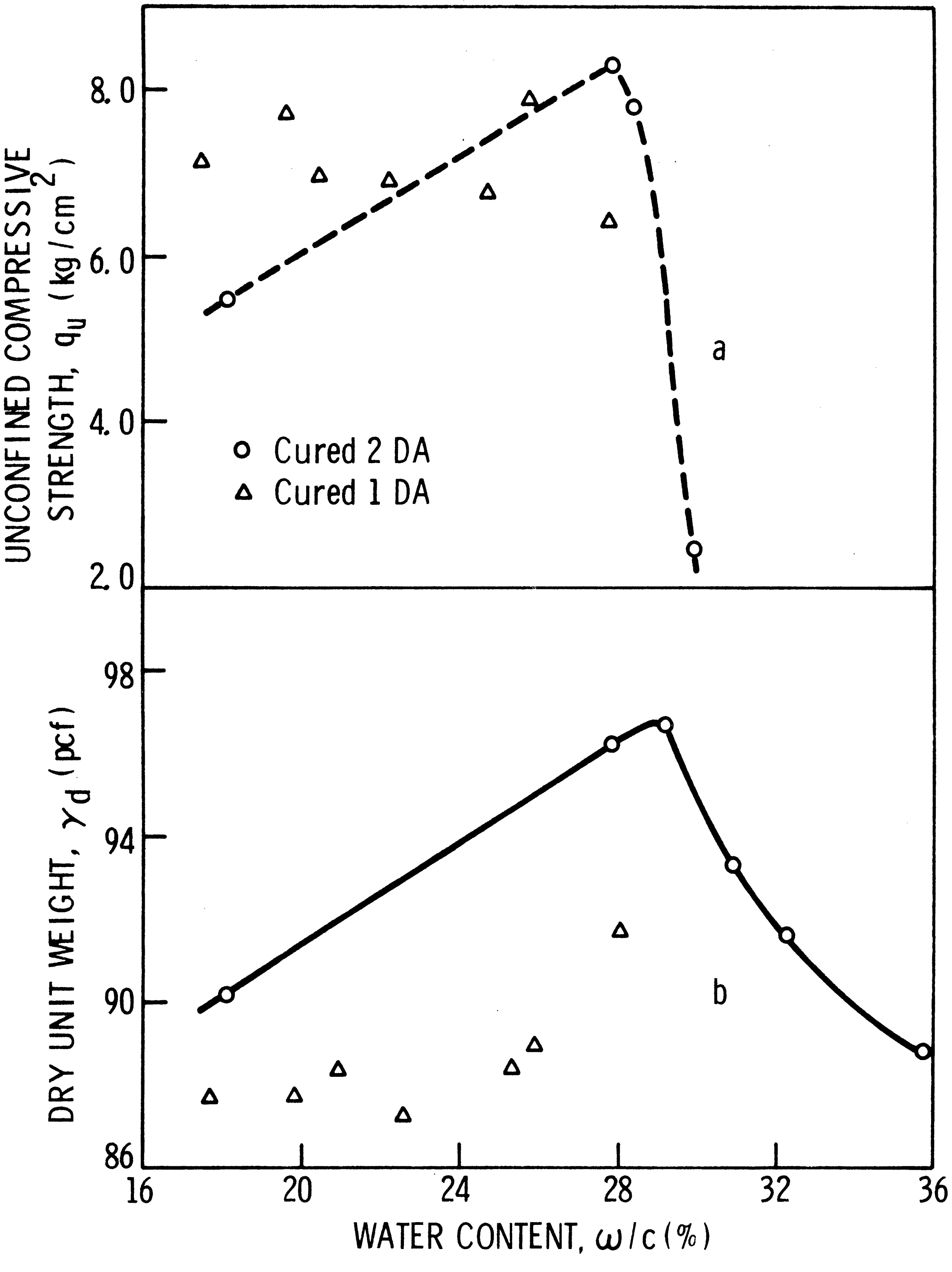


Figure 31. Compaction-strength behavior of unleached Mobile mud at a mud/sand ratio of 3:1.

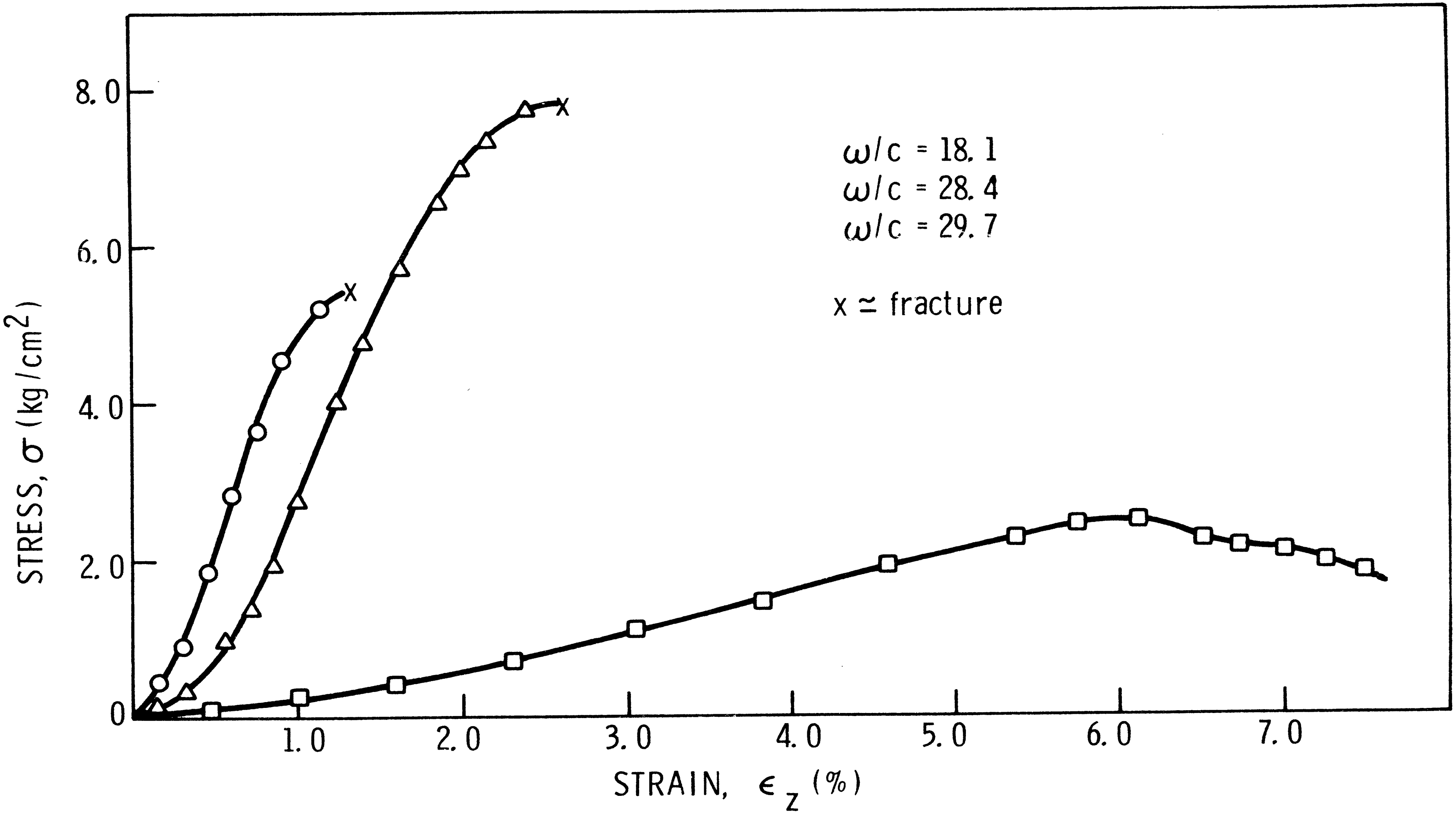


Figure 32. Typical stress-strain behavior during unconfined compression of compacted, unleached Mobile mud at a mud/sand ratio of 3:1 and a 2-day cure.

Curing time affected the test results significantly; no optimum moisture content was evident on samples tested one day after mixing at the desired moulding water content. Likewise samples cured for one day, regardless of moisture content, exhibited quite similar strengths.

Samples cured for two days prior to testing, on the other hand, behaved quite differently. The optimum moisture content was 29% (77% solids by weight). Strength increased slightly with increasing water content on the dry side of optimum, but fell off sharply with increasing water content on the wet side. The latter observation was substantiated by the fact that it was impossible to perform unconfined compression tests on samples compacted at moisture contents greater than 30%, because the samples were so weak that they slumped under their own weight.

The increase in plasticity with moisture content exhibited by samples cured for two days is illustrated by the stress-strain curves in Figure 32. For samples compacted dry of optimum, failure was brittle,occurring at strain levels increasing with moisture content. Failure in the sample wetter than optimum occurred at quite high strain levels by plastic flow rather than brittle fracture.

VI ANALYSIS AND DISCUSSION OF RESULTS

A. APPLICABILITY OF CONSOLIDATION MODELS TO RED MUDS

So far only the Terzaghi Consolidation Theory has been used to evaluate the data obtained in the present study. The theory appears to model the observed consolidation behavior adequately. The deformation-time curves, whether plotted to square root of time (Taylor's Fitting Method) or logarithm of time (Casagrande's Fitting Method), assume the anticipated shapes for almost all load increments.

Perhaps the simplest check on the validity of Terzaghi's Theory for any soil can be made by comparing the computed and measured values of permeability. This method is effective since permeability is the parameter in Terzaghi Theory which controls the time rate of consolidation and which can also be measured directly (and independently) during the consolidation test.

This check has been made on tests MCON-3 and PCON-1. The values of calculated and measured permeability are in quite close agreement, particularly for MCON-3 as shown in Table 12.

The only fact that leaves major doubt concerning the validity of Terzaghi's Theory is related to pore pressure measurements (conducted on MCON-5b and MCON-6). Although the existing pore pressure measuring system requires further modification to reduce compliance, there is an unexplained residual pore pressure at times greater than the predicted end of primary consolidation. This is the same observation made by Raymond which was discussed previously. Coupled with the fact that the relationship between void ratio and the logarithm of permeability is an approximately linear one (as shown in Figure 30) it seems logical to investigate the validity of Raymond's Non-linear Theory in modelling the consolidation behavior of Red Muds.

The applicability of any consolidation theory or model for predicting actual field settlements is another matter. This can only be checked by pilot field studies — a logical next step after completion of the laboratory testing program.

B. ANALYSIS OF ALTERNATIVE DEWATERING SYSTEMS

A major purpose of the testing program on red muds is to determine the feasibility of dewatering the mud by consolidation under externally applied loads. The review of past work (Section II) discussed several schemes or methods for dewatering the mud by combined processes of evaporation, decantation, and self drainage.

Undoubtedly some reliance must be placed upon these methods particularly during the early stages of dewatering when the solids content of the muds is too low to sustain any surcharge loading. On the other hand, once a critical solids content is reached consolidation under load becomes increasingly attractive. Several consolidation options are available; these are analyzed in a preliminary fashion in this report.

As a starting point for surcharge techniques, it has been assumed that the impounded slurry has been dewatered to a solids content of 60-70% by a combination of decantation, drainage and evaporation, as previously described (refer to Sec. II - C).

Two basic techniques of surcharging are considered. In the first, the partially dewatered mud is covered with an impermeable membrane which forms the base of a new 'lift' of fresh mud slurry. The total weight of the slurry above the membrane is effective in causing consolidation of the underlying mud. While this method minimizes the normal construction problems associated with the placing of surcharge, its major disadvantage is the imposition of one-way drainage within the consolidating layer. The resulting time necessary for consolidation is four times as long as for a double-drained layer of equal thickness.

The second technique involves the placing of permeable fill over the partially dewatered mud. Vertical sand drains (providing radial drainage) may or may not be included.

The time required to attain 90% of ultimate primary consolidation under a single load increment, using various surcharge schemes, has been computed by the method described by Richart (1957). The thickness of the mud layer was taken to be 20 feet. Two methods of mud handling were investigated. In the first, the mud contained only fine material; the second, included total processing plant tailings at a mud/sand ratio of 3:1. The coefficients of vertical permeability and consolidation were assigned typical values as determined in the experimental program. Since the coefficient of horizontal permeability is yet to be measured, two cases, that of equal horizontal and vertical permeability and horizontal permeability equal to 5 times the vertical, were examined. Sand drain spacing refers to the distance between two adjacent drains installed in an equilateral triangular pattern. The results of the computations are presented in Table 14.

It can be seen that drastic reductions in consolidation time are possible, depending on the relative permeabilities and choice of sand drain diameter and spacing. With the use of vertical sand drains dewatering times compare quite favorably to those reported by Vogt (1973) for the Deep DREW process (see Figure 13).

The total amount of surcharge and time needed to sufficiently dewater the mud layer have not been computed for several reasons. The final solids content required depends entirely on the purposes for which dewatering was initially undertaken, or upon the intended use of the stabilized mud lakes.

Furthermore, the age of the mud lake effects the amount of surcharge. At loads below the apparent preconsolidation pressure, the mud is quite incompressible, and little dewatering will occur.

Finally, it is very unlikely that the entire amount of surcharge required to produce the desired solids content can be applied at once, due to the low shear strength (and therefore bearing capacity) of the mud during the initial stages of dewatering. Determination of the shear strength vs. moisture content relationship is required in order to determine the allowable load increments to apply.

TABLE 14. TIME REQUIRED FOR 90% CONSOLIDATION OF 20-FOOT THICK LAYER OF RED MUD

DEWATERING SCHEME				TIME REQUIRED FOR 90% CONSOLIDATION	
				PURE MUD	MUD/SAND RATIO 3:1
PRELOADING WITH TOTAL SLURRY USING MEMBRANES (ONE-WAY DRAINAGE)				680	340
PRELOADING WITH PERMEABLE FILL	VERTICAL DRAINAGE ONLY (TWO-WAY)			170	85
	USING SAND DRAINS (COMBINED VERTICAL AND RADIAL DRAINAGE)	12" DIA. DRAINS AT 10 ft	$k_h=k_v$	55	27
			$k_h=5k_v$	15	7
		12" DIA. DRAINS AT 40 ft	$k_h=k_v$	155	80
			$k_h=5k_v$	-	-
		6" DIA. DRAINS AT 20 ft	$k_h=k_v$	130	65
			$k_h=5k_v$	70	35

Notes: For mud alone, $k_v = 1 \times 10^{-6}$ cm/sec
$c_v = 0.0054$ cm^2/sec

For 3:1 mud/sand, $c_v = 0.011$ cm^2/sec
$k_v = 1 \times 10^{-6}$ cm/sec

VII SUMMARY AND CONCLUSIONS

A. HIGHLIGHTS OF RESEARCH FINDINGS

This report only covers the results of the first year's study on the engineering properties and dewatering characteristics of red muds. The laboratory research has focused primarily on red muds from the Mobile plant; furthermore, several of the scheduled tests are either incomplete or yet to be run at this writing. These considerations should be borne in mind when reviewing the conclusions of the study to date. Nevertheless, some salient and interesting results have emerged from the red mud study which are summarized below:

1. A parametric variation type study was undertaken on the red muds rather than relying on tests on in-situ samples. Poor field sampling plus the opportunity to examine the influence of varying mud properties on mud management and dewatering strategies dictated this decision.
2. Red muds from Alcoa's Mobile and Point Comfort plants are not presently discharged to the mud lakes in a manner to optimize their dewatering and consolidation. No provision is made for example, for installation of drainage blankets, finger drains, compartmentalization of impoundments, etc.
3. The red mud tailings from Mobile and Point Comfort are basically ferrosilts containing 30 and 20 percent of clay-sized material (minus 2 microns). They would both be classified as ML — clayey or sandy, non-plastic, inorganic silts—under the Unified Soil Classification system.
4. Both the apparent, gradation and the plasticity of the red muds were very sensitive to the presence of dissolved solids. Not only were these index properties affected by dissolved solids, but so too were engineering properties such as shear strength and compressibility.
5. Although the red muds contained clay-sized material there was no evidence from mineralogic analyses for the presence of any clay minerals. The mineral constituents of the red muds appear to consist principally of hematite and complex

alumino-silicate compounds.

6. The consolidation characteristics of the red muds were affected by mud/sand ratio, dissolved solids, and duration of preconsolidation load. All these factors should be taken into account when designing an impoundment for storage and dewatering of tailings. Compression indices varied from 0.1 to 0.3, and coefficients of consolidation from $2\text{x}10^{-4}$ to $6\text{x}10^{-2}$ cm/sec^2 for the various muds tested.
7. Samples allowed to stand for some time (one month) in the slurry consolidometer exhibited a high apparent preconsolidation — about four times the actual preconsolidation pressure. This finding has important consequences for selecting the appropriate loading for in-situ consolidation.
8. The undrained shear strength of the red muds, as determined by vane tests, ranged approximately from 0.04 to 2 Kg/cm^2 for corresponding water contents between 60 and 40 per cent. Shear strength was likewise affected by mud/sand ratio, mud type and dissolved solids. Sensitivity or loss of strength on remolding averaged about 6 for most tests. Sensitivity was much higher, however, for leached samples and moreover appeared to be quite rate 'sensitive' in this case.
9. The permeability of the red muds varied regularly from 2 to $20\text{x}10^{-7}$ cm/sec over the range of void ratios of 0.8 to 1.4. Measured permeabilities agreed well with permeabilities predicted from the Terzaghi consolidation theory.
10. Compaction-strength behavior of the Mobile red mud (3:1 mud/sand ratio) was sensitive to time of cure after mixing. Samples cured for two days and then compacted according to Modified AASHO specifications exhibited a maximum dry density of 97 pcf and an optimum water content of 29 per cent. Unconfined compressive strength of compacted red mud samples varied from 4 to 8 Kg/cm^2, and fell off sharply on the wet side of optimum.
11. An analysis was made of alternative consolidation-dewatering systems including vertical drainage only, and vertical plus radial drainage. The effects of drain spacing, drain diameter, and ratio of horizontal to vertical permeability in the consolidating layer were investigated. Typical consolidation

times were calculated for these various systems. Use of vertical sand drains greatly reduced consolidation times. These results are tabulated in Table 14.

B. SUGGESTED DIRECTIONS FOR FUTURE RESEARCH

The first year of laboratory research on the red muds from Alcoa's Mobile and Point Comfort plants suggests several areas for further or additional research. Some of this research can be carried out in the laboratory, but a major portion will require pilot field studies and observation. Areas which have been identified for worthwhile future study include:

1. Determination of strength vs. water content relationships in order that surcharge loadings can be designed without risk of bearing capacity failures.

2. Further study of the apparent overconsolidation or preconsolidation phenomenon and the time effects associated thereof. This preconsolidation pressure must be exceeded before any significant consolidation can occur.

3. Determination of rates of consolidation for the case of a layer with horizontal finger drains.

4. Determination of optimal rate of surcharge (or consolidation load) application to avoid bearing capacity failure yet minimize consolidation times.

5. Design of an impoundment and mud disposal system to optimize dewatering and consolidation.

6. Determination of dessication drying characteristics of red mud.

7. Development of viscoelastic and viscoplastic models for modelling consolidation behavior of red muds.

8. Pilot field studies of surcharged red mud deposits instrumented with piezometers and settlement plates.

VIII ACKNOWLEDGMENT

The research described herein is part of a continuing study supported by a grant from the Alcoa Foundation. Marilyn Edwards assisted with preparation of samples and laboratory testing. The report was typed by Marcelle Storer.

REFERENCES

1. ASTM, 1974 Annual Book of ASTM Standards, Part 19: Soil and Rock; Building Stones; Peats, April, 1974.

2. Barden, L. (1965) "Consolidation of Clay with Non-Linear Viscosity," Geotechnique, v. 15, n. 4, Dec., pp. 345-362.

3. Biot, M. A. (1941) "General Theory of Three-Dimensional Consolidation," Journal of Applied Physics, vol. 12, pp. 155-164.

4. Biot, M. A. (1955) "Thory of Elasticity and Consolidation for a Porous Anisotropic Solid," Journal of Applied Physics, vol. 26, pp. 182-185.

5. Biot, M. A. (1956) "General Solutions of the Equations of Elasticity and Consolidation for a Porous Material," Trans, Journal of Appl. Mech., vol. 78, pp. 91-96.

6. Biot, M. A. & Willis, D. G. (1957) "The Elastic Coefficients of a Theory of Consolidation," Trans., Journal of Appl. Mech., vol. 79, pp. 594-601.

7. Brawner, Co O. & Campbell, D. B. (1973). The Tailing Structure and its Characteristics: A Soil Engineering's Viewpoint, Proceedings, 1st International Tailings Symposium, Tucson, Arizona, Miller Freeman Publications, pp. 59-102.

8. Casagrande, A. (1948) "Classification and Identification of Soils," Trans., ASCE, vol. 113, p. 901.

9. Davis, E. H. & Raymond, G. P. (1965) "A Non-Linear Theory of Consolidation," Geotechnique, vol. 15, no. 2, June, pp. 161-173.

10. D'Appolonia, E. et al (1973). Abandonment of Tailings Facilities, Proceedings, 1st Intl. Tailings Symposium, Tucson, Arizona, publ. by Miller Freeman Publications, pp. 571-605.

11. Gibson, R. E. & Lo, K. Y. (1961) " A Theory of Consolidation for Soils Exhibiting Secondary Compression," Norweg. Geot. Inst. Publ. #41.

12. Guerra, F. (1973). Characteristics of Tailings from a Soils Engineer's Viewpoint, Proceedings, Intl. Tailings Symposium, Tucson, Miller Freeman Publications, pp. 102-137.

13. Hamel, J. V. & Gunderson, J. W. (1973). "Shear Strength of Home Stake Slimes Tailings," Journal of Soil Mech. and Foundations Division, ASCE, Vol. 99, No. SM5, pp. 427-431.

14. Jenny, F. C. (1973). Ferrosilt (Red Mud): Geotechnical and Soil Mechanics Considerations, unpublished report.

15. Johnson, S. J. (1970). "Foundation Precompression with Vertical Sand Drains," Journal of Soil Mech. and Foundations Division, ASCE, Vol. 96, No. SM7, pp.

16. Johnston, C. E. (1973). Tailings Disposal: Its Hidden Costs, Proceedings, 1st Intl. Tailings Symposium, Tucson, Arizona, Publ. by Miller Freeman Publications, pp. 762-815.

17. Kenney, T. C., Moum, J., & Berre, T. (1967) "An Experimental Study of Bonds in a Natural Clay," Proc., Geot. Conf., Oslo, pp. 65-69.

18. Lo, K. Y. (1961) "Stress-Strain Relationship and Pore Water Pressure Characteristics of a Normally Consolidated Clay," V Int. Conf. Soil Mech. and Fndn. Engg., Proc., Paris, vol I,

19. Miners, K. A. (1973). Alcan's Experience with Disposal of Red Mud Tailings from the Bayer Ore Process, Proceedings, 1st Intl. Tailings Symposium, Tucson, Arizona, publ. by Miller Freeman Publications, pp. 553-562.

20. Mitchell, J. K., Greenberg, J. A. & Witherspoon, P. A. (1973) "Chemico-Osmotic Effects in Fine-Grained Soils," Jnl Soil Mech. & Fndn. Div., ASCE, vol. 99, no. SM4, April, pp. 307-322.

21. Paduana, J. A. (1966) "The Effect of Type and Amount of Clay on the Strength and Creep Characteristics of Clay-Sand Mixtures," thesis presented to the University of California, Berkeley, in partial fulfillment of the requirements for the Doctor of Philosophy.

22. Pettibone, H. C. & Kealy, C. D., "Engineering Properties of Mine Tailings," Journ. of Soil Mech. and Fndn. Div., ASCE, vol. 97, No. 9, pp.

23. Pincus, A. G. (1968). "Wastes from Processing of Aluminum Ores," Preceedings, Symposium on Mineral Waste Utilization, U. S. Bureau of Mines & IIT, pp. 40-49.

24. Raymond, G. P. (1966) "Laboratory Consolidation of Some Normally Consolidated Soils," Can. Geot. Jnl. vol. 3, no. 4, Nov., pp. 217-234.

25. Raymond, G. P. (1969) "Consolidation of Deep Deposits of Homogeneous Clay," Geotechnique, vol. 19, no. 4, Dec., pp. 478-494.

26. Richart, F. E., Jr. (1957) "A Review of the Theories for Sand Drains," Jnl, Soil Mech. & Fndn. Div., ASCE, vol. 83, no SM3, July, 38pp.

27. Schiffman, R. L. (1960) "The Consolidation of Fine-Grained Soils with Time-dependent Loading and Variable Permeability," PhD thesis, RPI, 137 pp.

28. Schiffman, R. L. & Gibson, R. E. (1964) "Consolidation of Nonhomogeneous Clay Layers," Jnl, Soil Mech. & Fndn. Div., ASCE, vol. 90, no. SM5, Sept., pp. 1-30.

29. Skempton, A. W. (1953) "The Colloidal 'Activity' of Clays," Proc., III Intnat'l Conf. Soil Mech. & Fndn. Engg., Switzerland, vol. I, pp. 57-61.

30. Smith,E. S. (1969),Tailings Disposal and Liquifaction, Transactions, Soc. Mining Engineers, AIME, vol. 244, pp.179-186.

31. Smith, E. S. (1973), Tailings Disposal: Failures and Lessons, Proceedings, 1st Intl. Tailings Symposium, Tucson, Arizona, Miller Freeman Publications, pp. 356-376.

32. Swaisgood, J. R. and Toland, G. C. (1973), Control of Water in Tailings Structures, Proceedings, 1st Intl. Tailings Symposium, Tucson, Arizona, publ. by Miller Freeman Publications, pp. 138-163.

33. Tozzoli, A. J. and York, D. L. (1973), Water Used to Preload Unstable Soils, Civil Engineering, vol. 43, no. 8, pp.56-59.

34. Vogely, W. A. (1968), Economic Factors of Mineral Waste Utilization, Proceedings, Symposium on Mineral Waste Utilization, Chicago, pp.7-19.

35. Vogt, M. F. (1973), Development Studies on Dewatering of Red Mud, unpublished report, Kaiser Aluminum & Chemical Corp.

36. Wahls, E. H. (1962) "Analysis of Primary and Secondary Consolidation," Jnl, Soil Mech. & Fndn. Div., ASCE, vol. 88, no.SM6, pp. 207-231.

37. Whitman, R. V. (1970), "Hydraulic Fills to Support Structural Loads," Jnl, Soil Mech. & Fndn. Div., ASCE, vol. 96, no. SM7, pp.