Bulletin 676

Conventional Versus Developing Processes of Phosphatic Clay Disposal:

A Technical Evaluation

By Jerry T. McLendon, James R. Boyle, Jr., and John W. Sweeney

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF MINES

Bulletin 676

Conventional Versus Developing Processes of Phosphatic Clay Disposal: A Technical Evaluation

By Jerry T. McLendon, James R. Boyle, Jr.,
and John W. Sweeney

UNITED STATES DEPARTMENT OF THE INTERIOR
William P. Clark, Secretary

BUREAU OF MINES
Robert C. Horton, Director

This research was carried out under a memorandum of agreement between the Bureau of Mines, U.S. Department of the Interior, and the Florida Institute of Phosphate Research.

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

Library of Congress Cataloging in Publication Data

McLendon, Jerry T.

Conventional versus developing processes of phosphatic clay disposal.

(Bulletin; 676)

"This research was carried out under a memorandum of agreement between the Bureau of Mines, U.S. Department of the Interior, and the Florida Institute of Phosphate Research."

Bibliography: p. 25

Supt. of Docs. no.: I 28.3:676

1. Clay industries—Waste disposal. I. Boyle, James R. II. Sweeney, John W. III. United States. Bureau of Mines. IV. Florida Institute of Phosphate Research. V. Title. VI. Series: Bulletin (United States. Bureau of Mines); 676.

TD899.C57M37 622'.33'64 84-600110

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS—Continued

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

acre-ft	acre-foot	lb	pound
ft	foot	m	meter
gal/min	gallon per minute	m/s	meter per second
h	hour	mg/L	milligram per liter
in	inch	ppm	part per million
kN/m^2	kilonewton per square meter	ton/h	ton per hour
$kN{\cdot}m^2/yr$	kilonewton per square meter per year	yr	year

KEY TO LOCATIONS

AMAX	BF–1
Agrico Mining Co.	Boyette B–1 Boyette B–2 Boyette B–5 Carmachael Property pit 9
Brewster Phosphates	Haynsworth H–1 Haynsworth H–2 Lonesome L–1 Lonesome L–2
Gardinier Inc.	Fort Meade A (G–A)
International Minerals & Chemical Corp. (IMC).	Achan A–4 Clear Springs CS–2 Noralyn N–2 Noralyn N–4 Greenbay (GB)
Mobil Chemical Co.	Fort Meade FM–1 Homeland HO–2 Homeland HO–3
Swift-Mobil Chemical Co.	Fort Meade Varn (V)

CONVENTIONAL VERSUS DEVELOPING PROCESSES OF PHOSPHATIC CLAY DISPOSAL: A TECHNICAL EVALUATION

By Jerry T. McLendon,[1] James R. Boyle, Jr.,[2] and John W. Sweeney[3]

ABSTRACT

The proper disposition of phosphatic clays has been the subject of research and debated for years by phosphate producers, State and Federal research agencies, regulatory authorities, and environmentalists. To date, no "universal" solution exists for the ultimate disposl of phosphatic clays. This Bureau of Mines report examines the state of conventional clay disposal technology and reviews the technical progress of innovative alternatives. Twenty impoundment sites were investigated by the Bureau of Mines using geotechnical methods and laboratory analysis of cored samples. In addition, quasi-static cone penetrometer soundings were conducted to define clay and/or sand-clay interfaces en masse. Samples of the top, middle, and bottom hole segments were obtained at each station for laboratory studies of clay densities, pore fluids, plasticity, and mineralogical properties.

The results of this study support the continued use of *initial* clay settling impoundments but emphasize the need for "in-line" systems to reduce the initial volumes of plant-generated phosphatic clays. The effective use of sand tailings is also encouraged to promote further consolidation of clays via self-weight stressing, sand-clay admixtures, and/or surcharging sand caps.

INTRODUCTION

The disposition of phosphatic clays has been the subject of many discussions and debates by environmentalists, regulatory authorities, and industry officials as to the "proper" method of disposal. To date, an estimated 75,000 acres have been dedicated to the storage and final disposition of phosphatic clays in the central Florida phosphate district. A typical impoundment often encompasses 200 to 800 acres with dikes ranging from 40 to 60 ft in height. These voluminous slurries generated by the phosphate industry are viewed as being potentially hazardous by those opposed to conventional methods of storage. To some, the "universal" solution to the problem is the *immediate* storage of phosphatic clays below natural ground level in mine cuts to subsequently reduce the risk of dam failure. However, even with the most recent scientific advances this seems neither technologically nor economically feasible. A major obstacle to below-ground-level storage is that large volumes of process clay slurry (3% to 5% solids) will initially overfill the space originally occupied by the in-place phosphate matrix and overburden materials (*1*, pp. 4–15).[4] A process to consolidate this initial slurry to approximately 35% clay solids would result in only a partial solution to below-ground-level storage for most phosphatic clays as this assumes that only the 35% clay solids are placed in the excavated mine cuts, omitting the overburden and tailing sands. Generally, tailing sands and/or overburden materials are used in the final stages of reclamation to "cap" the surface of the consolidated clays. The superimposed weight of this cap promotes further consolidation of the clays and slightly elevates the area to provide surface drainage. Although the industry and scientific community have demonstrated several promising alternatives to conventional disposal, no "universal" solution has been developed that totally eliminates initial impoundments.

This report examines both the conventional settling and consolidation method and viable alternatives for the ultimate disposal of phosphatic clays. Much of the data used in this report was generated by industry R&D groups and by private research consultants. Where insufficient data were available or verifiable documentation was lacking, the Bureau of Mines conducted geotechnical investigations to update the data base. In this study 20 impoundments that used both conventional and developing clay disposal techniques were investigated. Each impoundment site was characterized to emphasize the nature of the stored phosphatic clays and to identify the difficulties in devising a "universal solution" to the problem of phosphatic clay disposal.

[1] Minerals engineer.
[2] Mining engineer.
[3] Supervisory mining engineer.
Tuscaloosa Research Center, Bureau of Mines, University, AL.
[4] Italicized numbers in parentheses refer to items in the list of references preceding the appendix.

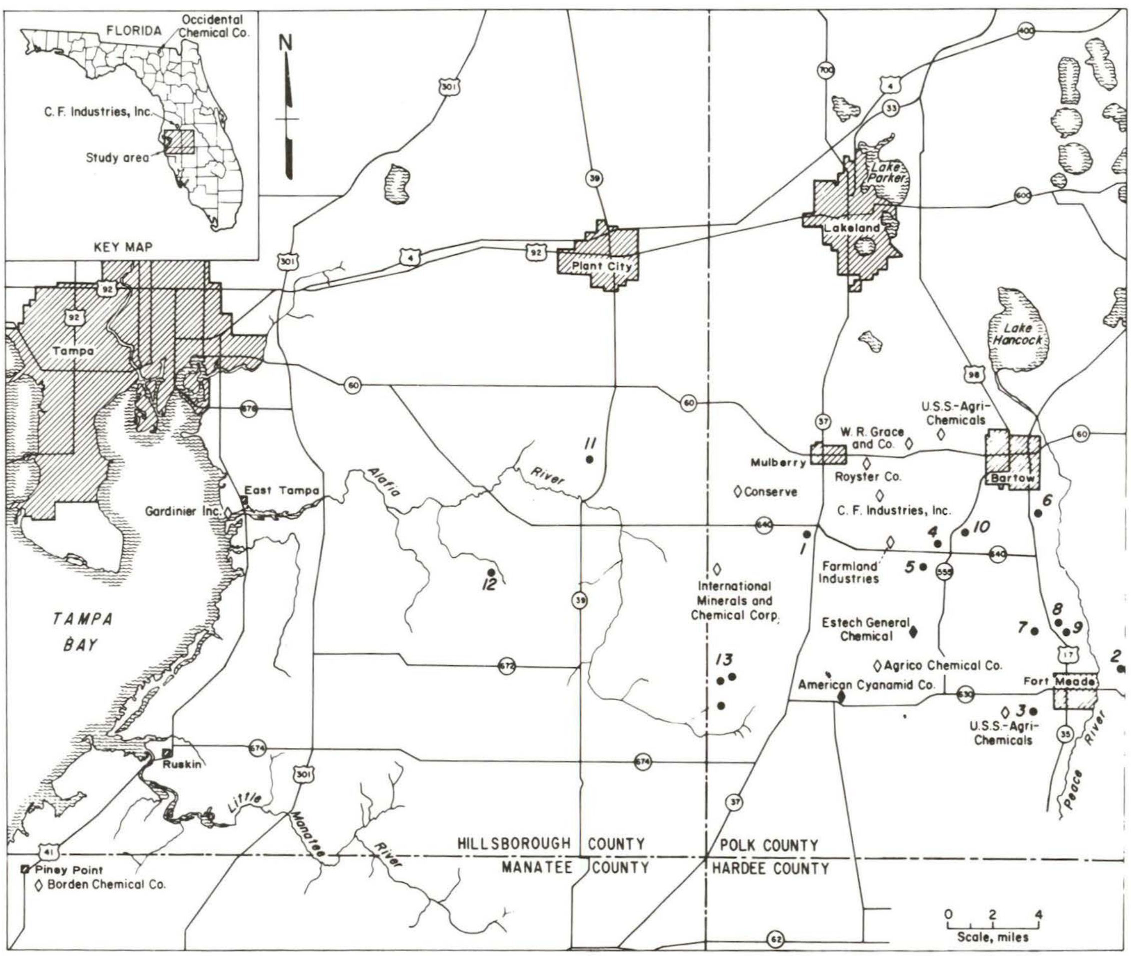
ACKNOWLEDGMENTS

The authors of this report wish to acknowledge the support of the Florida Institute of Phosphate Research in sponsoring and funding this investigation. In addition, several phosphate companies furnished basic research data and provided sampling sites which contributed greatly to the successful completion of this study. A sincere appreciation is extended to the following companies: Agrico Mining Co., AMAX Phosphate, Inc., Brewster Phosphates, Inc., Gardinier, Inc., International Minerals and Chemical Corp. (IMC), and Mobil Chemical Co.

A special appreciation is also extended to Dr. J. E. Lawver (IMC), Thomas P. Oxford (Zellars-Williams, Inc.), Richard Powers (Bromwell Engineering, Inc.), Lee Cawley (IMC), and Robert Swanson (AMAX Phosphate, Inc.) for their contributions and technical assistance in providing base-line data used in this study.

SELECTION OF SAMPLING SITES

This investigation was conducted for the purpose of (1) evaluating the geotechnical properties of phosphatic clays that have been stored and allowed to settle naturally in conventional impoundments and (2) evaluating newly developed processes and viable alternatives to clay disposal. In accomplishing these objectives, representative samples were obtained from impoundments throughout the central Florida phosphate district. The numbers shown on the map in figure 1 identify the test sites, which represent either a discrete impoundment or a series of impoundments with special characteristic features. Each site illustrates a variety of conditions existing at the time of disposal and generally reflects the basic technology then available. Test sites were selected on the basis of—



LEGEND

◊ Active chemical plants and phosphogypsum stacks
♦ Inactive chemical plants and phosphogypsum stacks
1 International Minerals & Chemical Corp. Inc. (A-4)
2 Mobil Chemical Company, Inc. (FM-1)
3 Gardinier, Inc.
4 International Minerals & Chemical Company, Inc. (N-4)
5 International Minerals & Chemical Company, Inc. (Greenbay)
6 International Minerals & Chemical Company, Inc. (CS-2)
7 Swift-Mobil Chemical Companies (Varn)
8 Mobil Chemical Company, Inc. (HO-2)
9 Mobil Chemical Company, Inc. (HO-3)
10 International Minerals & Chemical Company, Inc. (N-2)
11 Agrico Chemical Company, Inc. (Carmacheal)
12 Agrico Chemical Company, Inc. (Boyette B-1, B-2, B-5)
13 Brewster Phosphates, Inc. (Haynsworth, Lonesome)

FIGURE 1.—Impoundment sampling sites of central Florida phosphate district.

1. Age of clay deposition.
2. Geographical distribution of the impoundment site.
3. Reported solids content of the disposed clay.
4. Special applications of sand tailings with clay solids.
5. Slurry input rate and total storage capacity of the impoundment.
6. Unique settling characteristics of specific clays.
7. Reference of the ambient water table to impoundment base (above versus below-natural-ground-level storage).

SAMPLING PROCEDURES AND GEOTECHNICAL TEST METHODS

Between 6 and 12 stations were selected for sampling at each impoundment site. The number of sampling stations selected depended primarily on areal extent, access to the area, and general variance of the sample "suite." At each station, three discrete segments were obtained that represented the upper, middle, and bottom hole depths of the material sampled. In addition, clay solids were obtained for laboratory determination of clay solids content, crystal structure, chemical composition of extracted pore fluids, and plasticity. Geotechnical data were also obtained as a means of comparing the fundamental properties of clay solids from each impoundment. There data were acquired by using the following tests and laboratory procedures:

1. Quasi-static cone penetrometer soundings (Dutch cone penetrometer, DCP).
2. Coring logs.
3. Pore pressure measurements.
4. Pore fluids analysis.
5. Plasticity index.
6. Mineralogical determinations.

QUASI-STATIC CONE PENETROMETER TESTS

The quasi-static cone penetrometer soundings were used to identify and record unconformities of subsurface "layers" within the clay impoundments and to profile impoundment sites, delineate zones of consolidated clay, and prevent intersecting overburden and/or spoil crests. Historically, the "cone penetrometer" was used early in the 1930's in Europe in an effort to identify soil profiles for foundations and construction footings (*2*). This early device employed a cone tip with a 60° apex angle, affixed to a rod which was pushed into the soil horizon to determine axial stresses during penetration.

Today, this device has been modified to include a continuous recording pressure transducer which is incorporated within the cone tip and used in conjunction with a movable friction sleeve with an attached strain gauge. This modification, when electrically coupled to a strip chart recorder, continuously records cone tip stresses and sleeve friction of the soil or clay layers being penetrated. Additional rods can be joined to extend the penetration to depths which often exceed 100 ft. Ratios of sleeve friction (f_s) to cone tip resistance (Q_c) are used to relate changes in soil profiles. Figure 2 shows a computer-generated plot of the f_s:Q_c ratio in a clay impoundment area with respect to penetration depth. An extrapolated baseline at point *A* correlates core log determinations associated with sand, whereas point *B* is indicative of variations in clay solids concentrations. Conventional core logs indicated that the profile from 0 to

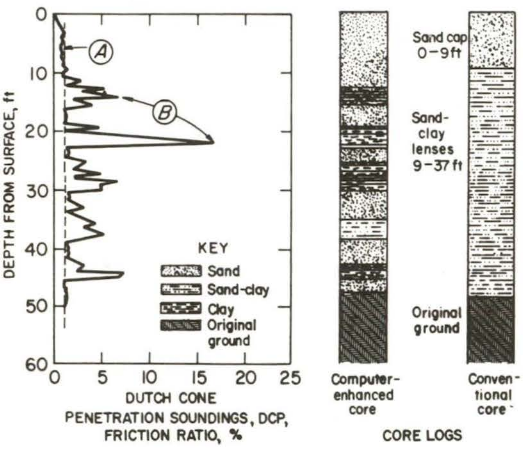


FIGURE 2.—Correlation of core logs with Dutch cone penetrometer soundings.

9 ft contains sand tailings, while the 9- to 37-ft section contains consolidated clays with intersecting sand lenses. Computer-enhanced core logs of the impoundment illustrate greater detail of sand-clay lenses with regard to the density and consistency of a unit.

Generally, when using the DCP for estimating bearing strength, the f_s to Q_c values are meaningful only when the cone tip and sleeve are both located in the same soil layer and are above the ambient water table. However, for quantitative purposes, in this investigation the f_s:Q_c ratio was used to distinguish interfacial boundaries of soil (clay-sand) layers and variances in clay consolidation. These are relative values and are not used to extrapolate or estimate bearing strengths of clays.

DCP AND CORE LOG TESTS

A composite profile, derived from collective DCP soundings, was used to depict the general nature of each impoundment. This profile subsequently was enhanced via computer graphics to show density variations within discrete clay layers. This information was used to quantitatively relate permeability to total drainage of the clay-water system. Figures in the appendix illustrating the DCP soundings are referenced throughout the text.

Occasionally, hand-driven mechanical cone soundings were used in areas that were inaccessible or in newly developed impoundments with low solids content. These tests were also used to profile sand-filled impoundments, which often required up to 75 lb of driving force to penetrate to the necessary depths.

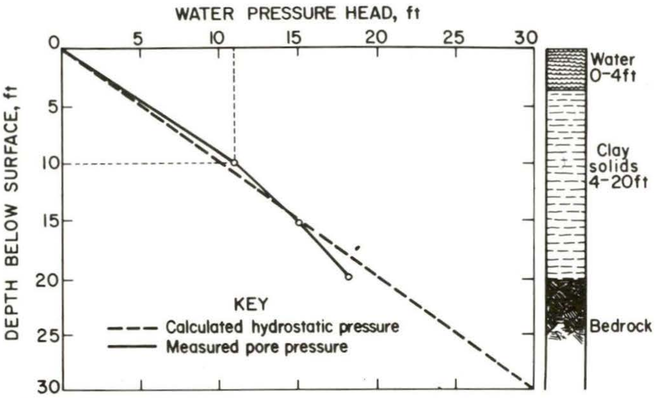


FIGURE 3.—Pore pressure measurements versus hole depth.

PORE PRESSURE TESTS

Pore pressure readings were obtained at selected impoundment sites in the immediate vicinity of the sampling stations. Pore pressure measurements relate the manner in which fluid pressures dissipate within the impounded mass. In general, the existence of pore water pressures near hydrostatic pressure is indicative of a system near equilibrium. Hence, the degree of consolidation may be estimated from data relating pore water pressures to hydrostatic pressure gradients. Figure 3 illustrates in situ pore pressure measurements (pressures expressed in feet) and calculated hydrostatic pressures.

At a depth of 10 ft the pore pressure is slightly above (11.0 ft, head) hydrostatic pressure, which indicates that a slight driving force exists for further consolidation. Below 10 ft in depth the self-weighting force of the slurry has approached equilibrium. In this instance, standing water was noted on the surface to a depth of 4 ft, where the water-clay interface was contacted. Site-specific measurements are shown throughout the text to describe each impoundment.

PORE FLUIDS ANALYSIS

Samples of pore pressure fluids were extracted from samples obtained at the mid-level depths of the clay column. Small volumes of deionized water were slurried with consolidated clay solids and allowed to settle and equilibrate for 21 days. Fluids from these samples were extracted and analyzed on a Dionex Ion Chromatograph model 16[5] for anion and cation determinations. This unit is capable of measuring single and multivalent anion and cation concentrations of 1 ppm. As a result, these data were used to relate electrolyte content of the fluids with mineralogical data of the clay solids, where the electrolytic exchange capacities of slurries might influence settling characteristics of the clay solids. It was earlier assumed that a correlation could be made regarding the interaction of clay particles with the electrolytic properties of the pore fluids, which in turn might ultimately influence clay settling rates. Bureau of Mines tests (*3*) have indicated that certain clays that are calcium exchanged, i.e., calcium substituted for the original cation, require less polymer dosage to settle clay solids than clay particles with calcium deficiency. The data in table 1 do not reflect such a correlation but do add to the overall data base. Calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), and potassium (K^{+}) are the common cations found in most soils in order of decreasing abundance, while sulfate (SO_4^{-2}), chloride (Cl^{-}), phosphate (PO_4^{3-}), and nitrate (NO_3^{-}) are the most common anions (*4*, p. 129). Values in table 1 follow this general rule and hence do not reflect a significant variance.

Table 1.—Pore fluid analysis of impounded phosphatic clays

CATIONS IN SOLUTION, MG/L

Sample location	Ca	Mg	Na	K	Li	NH_4
Agrico:						
B–2	51.64	16.96	6.20	1.48	ND	0.27
B–5	31.32	3.95	3.76	2.77	ND	ND
Brewster:						
H–1	56.83	23.82	2.83	.54	ND	ND
L–1	77.06	27.96	2.60	.83	ND	ND
Gardinier G–A	64.00	17.37	8.60	.39	ND	1.04
IMC:						
A–4	48.64	13.97	5.39	1.79	ND	ND
CS–2	60.34	15.84	8.06	1.65	ND	.47
N–2	70.92	25.70	12.01	.63	.08	.17
N–4	112.72	40.76	20.61	1.21	ND	ND
Mobil:						
FM–1	82.14	29.47	7.71	1.32	ND	ND
HO–2	81.26	29.63	9.18	.83	ND	ND
HO–3	79.09	27.24	12.74	1.95	ND	.16
Varn (V)	61.72	24.03	9.99	1.48	ND	1.07

ANIONS IN SOLUTION, MG/L

Sample location	F	Cl	PO_4	NO_3	SO_4
Agrico:					
B–2	2.53	3.31	0.183	4.33	38.65
B–5	1.20	4.59	2.27	7.85	29.48
Brewster:					
H–1	2.14	2.54	.19	ND	73.20
L–1	1.39	2.85	.22	.29	110.35
Gardinier G–A	2.87	3.43	1.58	ND	37.44
IMC:					
A–4	2.43	3.01	ND	ND	13.29
CS–2	1.79	4.88	.76	.15	31.86
N–2	1.35	2.75	ND	ND	68.62
N–4	1.26	3.99	.30	ND	164.00
Mobil:					
FM–1	1.92	6.04	.17	1.02	138.18
HO–2	1.32	1.87	ND	ND	87.69
HO–3	1.93	4.34	.24	ND	113.22
Varn (V)	1.80	3.86	.27	ND	46.38

ND Not detected.

PLASTICITY INDEX

According to reports by Bromwell Engineering, the consolidation properties of phosphatic clays are closely linked to the plasticity index (PI) of the impounded clays. As the PI increases, the consolidation properties decrease. A PI of 80 or under would be rated good, 80 to 120 would be medium, and over 120 would be poor with regard to settling and consolidation properties (*5*).

A composite sample from each of 12 phosphatic clay settling areas was tested to determine the liquid and plastic limits. The plasticity index[6] for each sample was calculated from the test results and is presented in table 2.

[5] Reference to specific products does not imply endorsement by the Bureau of Mines.

[6] The plasticity index is the range over which a soil is plastic and is represented by the difference between the liquid and plastic limit. According to "Soil Testing for Engineers" by T. W. Lambe and R. V. Whitman (MIT, 1951), "The liquid limit is the water content at which the soil has such a small shear strength that it flows to close a groove of standard width when jarred in a specified manner. The plastic limit is the water content at which the soil begins to crumble when rolled into threads of specified size."

Table 2.—Liquid limit, plastic limit, and plasticity index of composite phosphatic clay samples

Company	Liquid limit	Plastic limit	Plasticity index
Mobil:			
FM–1	187	57	130
HO–2	150	50	100
HO–3	189	74	115
Varn (V)	169	62	107
IMC:			
CS–2[1]	91	66	25
Greenbay (GB)	151	35	116
N–2	138	57	81
N–4	155	48	107
Agrico:			
B–1	153	55	98
B–2[1]	55	23	22
B–5[1]	30	22	8
Gardinier: G–A	161	52	109

[1] Abnormal amount of +150 material (sand) in sample.

The plasticity index for samples without sand ranged from 81 to 130, falling into the medium to poor range. This would indicate that a mixture of sand and clay would exhibit much better consolidation than clay alone. However, this is not the case. The clay particles tend to encapsulate the sand grains, keeping the grains apart, so that a sand-clay mix generally exhibits similar consolidation properties to clays alone. PI studies are being continuously updated by industry in an effort to create a body of data relating settling characteristics of clays to plasticity indexes.

MINERALOGY DETERMINATION

The mineralogy composition of clay solids stored in conventional impoundments is a valuable characteristic for use in determining the settling properties of any phosphatic clay slurry. The species of minerals present in any impoundment along with its relative abundance can greatly influence the rate of clay consolidation. Two investigators (*6–7*) have indicated that relatively minor amounts of attapulgite in a slurry can greatly hinder the natural settling of slurry mass. Attapulgite, with its needlelike structure, is difficult to settle when using both natural (gravity) and flocculating techniques and should be recognized as a "bad actor" in planning disposal systems. Consequently, X-ray diffraction (XRD) patterns were examined to quantify properties of impounded clay slurries and to correlate these findings with other data. XRD identifies the mineral species and quantifies the composition of each sample with regards to major, minor, and trace amounts present in a sample suite.

Table 3 summarizes mineralogical data; it shows montmorillonite and apatite as the major mineral constituents present in all clay samples tested, while quartz and the kaolin group compose the minor minerals. Trace amounts of wavellite, crandallite, microcline, and illite were also detected in most samples but are of lesser importance. Attapulgite, which is seen as more resistive to settling, is identified in all but samples A–4, G–A, and B–5. On a macroscopic scale, where clay slurries entering an impoundment are continuously changing, the bulk mineral ratios may change over a period of time, especially as mineral compositions fluctuate with changing feed matrix.

While the mineralogical data shown in table 3 cannot conclusively identify abnormal settling characteristics for impounded slurries, slurries with minor to trace amounts of attapulgite do tend to resist settling as opposed to slurries with no detectable attapulgite. Under laboratory conditions, using small cylinder tests, the attapulgite does have a deleterious effect on clay slurry settling rates as opposed to commercial impoundments, where filling rates, volumetric balances (input-output), and impoundment geometries are considered predominant factors.

XRD patterns identifying mineral suites from each impoundment are on file with the Florida Institute of Phosphate Research Bartow, FL, for further reference.

Table 3.—X-ray diffraction analysis of mineral components of impounded phosphatic clays

	IMC				Mobil				Gardinier G-A	Agrico		Brewster	
	A–4	CS–2	N–2	N–4	FM–1	HO–2	HO–3	Varn		B–2	B–5	H–1	L–1
Montmorillonite	M	M	M	M	M	M	M	M	M	M	M	M	M
Apatite	M	M	M	M	M	M	M	M	M	M	m	M	M
Quartz	m	m	m	m	m	M	m	m	M	M	M	m	M
Kaolin group	m	m	m	m	m	m	m	m	m	m	m	m	T
Illite	T	T	T	T	T	T	T	T	m	T	m	T	T
Attapulgite	ND	m	m	m	m	m	m	m	ND	T	ND	m	m
Dolomite	m	ND	T	T	T	T	T	T	T	T	ND	m	T
Wavellite	ND	T	T	T	T	T	T	T	m	T	T	T	T
Crandallite	T	T	T	T	T	T	T	T	T	T	T	T	T
Microcline	T	ND	T	T	ND	T	T	ND	T	T	T	T	T

NOTE—M = major; m = minor; T = trace; ND = not determined.

CONVENTIONAL CLAY DISPOSAL

Natural settling using conventional impoundments has been the most widely used process for disposing of phosphatic clays in the central Florida phosphate district. This process is simple and direct in that 40- to 60-ft dikes are constructed, often around mined-out areas comprising 200 to 800 acres, and are subsequently filled with untreated clay slurries of 3% to 5% solids. These slurries exit the phosphate washers and beneficiation plant at 20,000 to 80,000 gal/min. Most impoundments are designed for 1- to 2-yr initial storage capacities and are alternately used in tandem with other impoundments to allow periods of quiescent settling. Others are flow-through impoundments in which rejected plant slurries are flowed stagewise into a series of storage areas. This method allows the bulk of the solids to concentrate initially in the first impoundment, while the overflow is adjusted to discharge clear supernatant water for recycling or is flowed to a second impoundment for further sedimentation.

When mined-out cuts are used for storage, the clay slurries are trained through a network of windrows cast from overburden and/or mine spoil. Earthen baffles are constructed to create areas of undisturbed settling.

After a period of natural settling, most clays consolidate to 12% to 15% solids within 3 to 30 months (*8*). At this stage, most of the surface water is drained from the remaining solids, allowing the clays to desiccate, forming an impervious crust. This crust seals the top portion of the clay mass and offers some bearing strength. Generally, after sufficient crustal development, sand tailings and/or overburden materials are used to cap the clays. This cap serves to (1) transmit a vertical stress on the prethickened clays below to promote further consolidation, (2) improve stability of the reclaimed surface, and (3) provide growing media for vegetative cover (when using overburden soils). However, because of the slow consolidation rate of certain clays, this process may require 5 to 15 yr before the storage area can be totally reclaimed and the area returned to a useful state.

The following includes case histories that represent the classical nature of conventional impoundments found in the central Florida phosphate district. The age of each impoundment was established from the time filling with slurry was completed.

HISTORY, FIELD OBSERVATIONS, AND EVALUATIONS

IMC—Achan (A–4)

This impoundment represents the most recently used settling and storage area examined in this study. It encompassed approximately 336 acres with an average depth of 24 ft.

The dam surrounding the area was raised in 1965 to accommodate an additional 3 million tons of clay solids and was filled at an estimated rate of 300,000 to 500,000 tons of clay per year. Approximately 50% of the total holding capacity is aboveground, with the remaining storage in windrowed mine cuts below natural ground level. The natural water table for this area is estimated to be 10 ft below the base of the impoundment dam. The final filling was completed in 1976, and the area has since remained inactive.

The surface of this impoundment contained approximately 5 ft of liberated slurry water and was accessible only by airboat. The northern area was heavily vegetated with cattails and other aquatic vegetation. This type of vegetation occurs naturally on most settling areas where standing water exists. Electronic-sounding DCP measurements of the area were erratic, and hand-cone soundings had to be substituted. A penetration force of up to 30 lb was required to reach bottom depths, as shown in the appendix (fig. A–1). Field logs indicated a yellow-gray clay mass was prevalent throughout sampling.

Figure 4 shows plotted pore pressure recordings were slightly less than normal hydrostatic pressures at depths greater than 10 ft. This seems to indicate that interstitial fluid pressures within the clay solids have slightly dissipated near the bottom of the impoundment.

Data in table 4 show an average clay content of 18.4% solids by weight near the top of the clay column, 24.2% solids at middepth, and 28% solids at the bottom depth. This material was composed almost entirely of clay particles and averaged 23.6% solids for the entire profile.

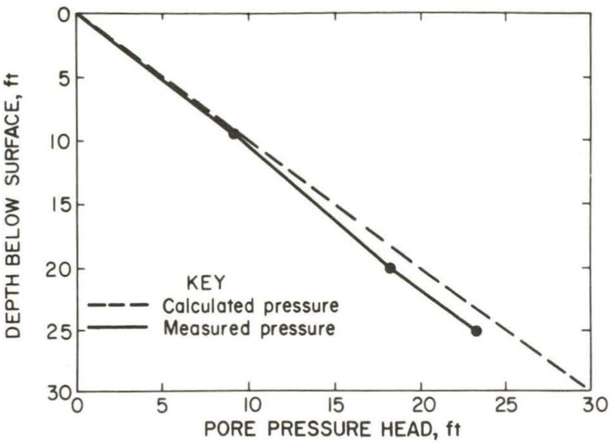


FIGURE 4.—Pore pressure measurements versus hole depth, IMC, Achan, (A–4).

Table 4.—Data summary of phosphatic clay solids, IMC, Achan (A–4)

Fraction sampled	C_s	%C	TS
Hole location A:			
Top	13.7	13.7	13.7
Middle	18.6	18.6	18.6
Bottom	32.5	32.5	32.5
Average	21.6	21.6	21.6
Hole location B:			
Top	17.7	17.7	17.7
Middle	24.3	24.3	24.3
Bottom	24.8	24.2	26.7
Average	22.3	22.1	22.9
Hole location C:			
Top	21.8	21.8	21.8
Middle	29.0	29.0	29.0
Bottom	27.7	27.7	27.7
Average	26.2	26.2	26.2
Hole location D:			
Top	18.1	18.1	18.1
Middle	25.0	25.0	25.0
Bottom	27.2	27.2	27.2
Average	23.4	23.4	23.4
Hole location E:			
Top	20.1	20.1	20.1
Middle	22.6	22.6	22.6
Bottom	26.5	26.5	26.5
Average	23.1	23.1	23.1
Hole location F:			
Top	19.3	19.3	19.3
Middle	25.7	25.7	25.7
Bottom	29.3	29.3	29.3
Average	24.8	24.8	24.8
Composite:			
Top	18.4	18.4	18.4
Middle	24.2	24.2	24.2
Bottom	28.0	28.3	28.3
Average	23.6	23.6	23.6

NOTE.—C_s = solids content of clay, %;
%C = clay in slurry, %;
TS = total solids in slurry, %.

Data tabulated in this table and all subsequent tables show the percentage of clay solids only (C_s), the percentage of clay within the total slurry (%C), and the total solids (TS) present in each sample set. Calculations for C_s show only the clay solids and do not reflect the influence of sand which may otherwise be present in the sample.

Mobil—Fort Meade (FM–1)

A complete filling history of this impoundment is unavailable since multiple inlets were in use. A 395-acre site, ranging from 13 to 26 ft deep, was originally designed for 40% above-ground-level storage. Field data indicate that much of the area was covered with approximately 4 ft of liberated water, which is characteristic of the early stage of consolidation. Cattails and saw grass covered the southeastern portion of the area; tailings sands had been pumped into the other, more consolidated areas.

Much of the area where tailings sands were pumped remained soft with poor crustal development. However, in some areas hand-driven cone soundings required up to 75 lb of penetration force to reach the uneven bottoms because of sand accumulations and spoil crests (fig. A–2).

Pore pressure data shown in figure 5 indicate that below 15 ft the fluid pressures in the lower extremities are slightly dissipated. Table 5 shows an upper clay content averaging 25.8% solids (C_s) with mid and bottom portions averaging 24.4% and 29.5% clay solids, respectively. Sand tailings were noted in several samples and are reflected under the TS heading, which represents percentage of sand plus clay in the total slurry. Generally, the middle depth values of the clay column show more consistent clay solids content as opposed to the top surface. This is primarily the result of surface desiccation and atmospheric conditions. In calculating solids content of the consolidated clay, the sand portion was removed to reflect "true" clay solids content only.

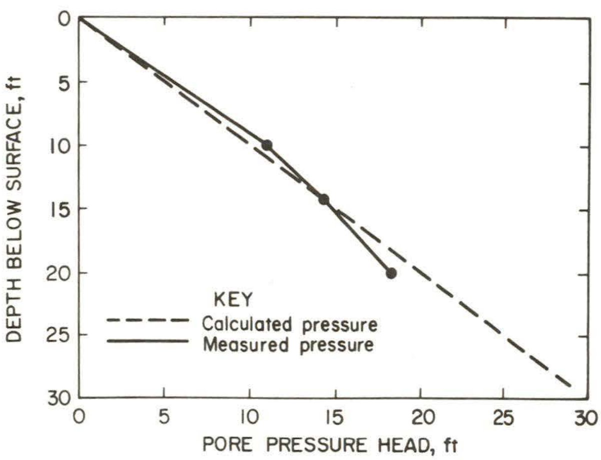


FIGURE 5.—Pore pressure measurements versus hole depth, Mobil, Fort Meade (FM–1).

Table 5.—Data summary of phosphatic clay solids, Mobil, Fort Meade (FM–1)

Fraction sampled	C_s	%C	TS
Hole location A:			
Top	32.0	30.6	34.9
Middle	37.6	30.5	49.3
Bottom	38.7	36.0	43.0
Average	36.1	32.4	42.4
Hole location B:			
Top	17.5	17.5	17.6
Middle	17.8	17.8	17.9
Bottom	32.4	32.4	32.5
Average	22.6	22.6	22.7
Hole location C:			
Top	17.2	17.2	17.3
Middle	21.2	21.2	21.2
Bottom	28.0	28.0	28.0
Average	22.1	22.1	22.2
Hole location D:			
Top	24.5	24.5	24.6
Middle	23.2	23.2	23.3
Bottom	26.4	26.4	26.4
Average	24.7	24.7	24.8
Hole location E:			
Top	27.8	27.8	27.9
Middle	23.1	23.1	23.2
Bottom	26.0	26.0	26.1
Average	25.6	25.6	25.7
Hole location F:			
Top	35.5	35.5	35.7
Middle	23.8	23.8	23.9
Bottom	25.3	25.3	25.4
Average	28.2	28.2	28.3
Composite:			
Top	25.8	25.5	26.3
Middle	24.4	23.3	26.5
Bottom	29.5	29.0	30.2
Average	26.6	25.9	27.7

NOTE.—C_s = solids content of clay, %;
%C = clay in slurry, %;
TS = total solids in slurry, %.

Gardinier—Fort Meade (G–A)

This impoundment was placed in service in 1966 and has a designed holding capacity of 6,500 acre-ft. It covers 233 acres with approximately 80% of the storage above natural ground level. Only one inlet was used to fill this rectangular impoundment, which was constructed almost entirely on level unmined land. Drainage from this area was enhanced through the impoundment bottom, peripheral ditches, and surface decantation. In addition, the ambient water table was approximately 10 ft below the base of the retaining dam, which contributed to bottom drainage. This impoundment had been idle since 1972 and capped with tailings sand and overburden materials after crustal development of 1 to 2 ft of thickened clays.

The entire area had abundant vegetation composed primarily of native grasses and small shrubs. Some standing water (1 to 4 in) was noted on the surface of the impoundment interior.

Bottom hole depths of the DCP rarely exceeded 16 ft throughout the sampling of this area. Graphical DCP data (fig. A–3) show a consistent clay mass throughout the vertical profile; bottom clays reached 45% to 46% solids during the 10 yr of quiescent settling.

The plotted data in figure 6 show that pore pressure readings measured below 5 ft were lower than hydrostatic pressures. This indicates considerable dissipation of the fluid pressures at depths near the impoundment bottom. The thickened bottom clays indicate that enhanced drainage occurred near the lower drainage boundary.

Table 6 shows that the average clay profile of the area was 37.5% solids. The upper portion of the clay column contained 34.7% solids, while the middepth and bottom

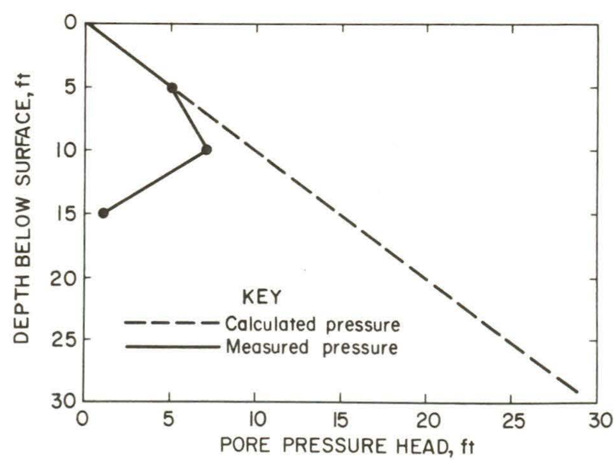


FIGURE 6.—Pore pressure measurements versus hole depth, Gardinier, Fort Meade (G–A).

Table 6.—Data summary of phosphatic clay solids, Gardinier, Fort Meade (G–A)

Fraction sampled	C_s	%C	TS
Hole location A:			
Top	34.9	34.9	34.9
Middle	34.7	34.7	34.7
Bottom	46.2	46.2	46.2
Average	38.6	38.6	38.6
Hole location B:			
Top	35.3	35.3	35.3
Middle	39.7	37.3	43.4
Bottom	42.1	41.9	42.3
Average	39.0	38.2	40.3
Hole location C:			
Top	35.5	35.5	35.5
Middle	36.0	36.0	36.0
Bottom	38.8	38.8	38.8
Average	36.8	36.8	36.8
Hole location D:			
Top	33.7	33.7	33.7
Middle	35.2	34.9	35.7
Bottom	42.2	42.2	42.2
Average	37.0	36.9	37.2
Hole location E:			
Top	34.8	34.8	34.8
Middle	33.1	33.1	33.1
Bottom	43.2	43.2	43.2
Average	37.0	37.0	37.0
Hole location F:			
Top	32.7	32.7	32.7
Middle	33.1	33.1	33.1
Bottom	45.5	45.5	45.5
Average	37.1	37.1	37.1
Hole location G:			
Top	36.7	36.7	36.7
Middle	35.5	35.5	35.5
Bottom	41.1	41.1	41.1
Average	37.8	37.8	37.8
Hole location H:			
Top	33.9	33.9	33.9
Middle	34.3	34.3	34.3
Bottom	42.1	42.1	42.1
Average	36.8	36.8	36.8
Composite:			
Top	34.7	34.7	34.7
Middle	35.2	34.9	35.7
Bottom	42.6	42.6	42.7
Average	37.5	37.4	37.7

NOTE.—C_s = solids content of clay, %;
%C = clay in slurry, %;
TS = total solids in slurry, %.

clays showed 35.2% and 42.6% solids, respectively. No sand was found to exist in the sampled clay mass. Apparently the total drainage of the clay system was sufficient to allow uniform crustal development in the upper clay zones, preventing mixing of the sand-overburden cap.

IMC—Noralyn (N–4)

The original construction of this area was completed in 1958 with a designed capacity of 10,400 acre-ft of storage. Approximately 60% of this storage has been above ground level since the dam height was increased in 1969–70. No sand was originally mixed with the impounded clays; however, in most samples examined, some sand was detected. This may have been the result of "mud wave" action as the sand cap was applied. Mud waving is a term used to describe movement of the impounded clay-sand mixture as shear stresses induced by the sand cap set up a heaving wave front during redistribution of the clay-sand solids.

Figure 7 shows that the pore pressures of the stored clay mass are greater than hydrostatic pressures. This seems to indicate that additional pressure is still available to induce further drainage of the clay system.

An analysis by some consultants indicates that mud waving is often beneficial to further liberation of entrained pore water as a result of the redistribution of the total stress between clay solids and pore fluids.

Table 7 shows that an average column of clay from this impoundment contains 33.4% solids by weight. The accompanying sand in the sample raised the average total solids content to 48.1% by weight. Field notes indicate that hand sampling of this area was not possible because of the high degree of consolidation. The interior portion of this area did, however, require airboats for sample acquisition, while the peripheral areas required the use of wide-track drilling equipment.

The soundings for this area were obtained by DCP and were electronically recorded. Computer-plotted data in figure A–4 show the results of continuous electric cone soundings. The irregular trace indicates horizons of

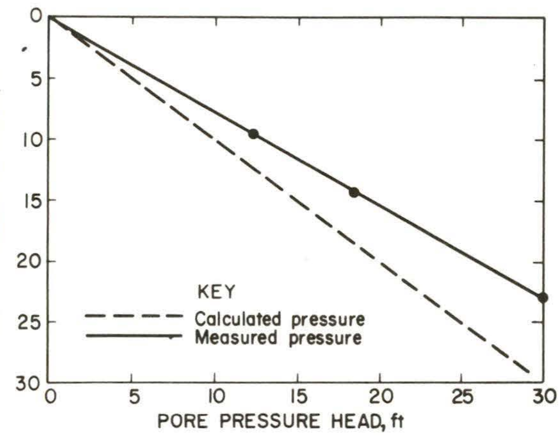


FIGURE 7.—Pore pressure measurements versus hole depth, IMC, Noralyn, (N–4).

Table 7.—Data summary of phosphatic clay solids, IMC, Noralyn (N–4)

Fraction sampled	C_s	%C	TS
Hole location A:			
Top	33.6	23.8	53.0
Middle	36.3	32.5	43.0
Bottom	38.6	32.7	48.1
Average	36.2	29.7	48.0
Hole location B:			
Top	29.1	23.0	43.9
Middle	33.8	32.2	36.9
Bottom	31.7	19.3	58.7
Average	31.5	24.8	46.5
Hole location C:			
Top	27.6	18.3	52.1
Middle	39.5	35.1	46.3
Bottom	44.0	39.8	49.4
Average	37.0	31.1	49.3
Hole location D:			
Top	35.8	33.7	39.6
Middle	35.8	33.4	40.2
Bottom	40.2	38.7	42.4
Average	37.3	35.3	40.7
Hole location E:			
Top	26.1	14.8	57.9
Middle	29.6	22.8	45.6
Bottom	35.1	25.4	53.0
Average	30.3	21.0	52.2
Hole location F:			
Top	19.4	9.0	62.8
Middle	32.6	25.7	46.8
Bottom	33.2	27.2	45.2
Average	28.4	20.6	51.6
Composite:			
Top	28.6	20.4	51.6
Middle	34.6	30.3	43.1
Bottom	37.1	30.5	49.5
Average	33.4	27.1	48.1

NOTE.—C_s = solids content of clay, %;
%C = clay in slurry, %;
TS = total solids in slurry, %.

varying resistance, which indirectly relate to sand-clay composition and density of the mass being penetrated. The accompanying core logs (right of the figure) represent the sand cap and various sand-clay anomalies encountered. These sand-clay lenses are indicative of the interaction of the sand cap with the prethickened clays during redistribution of the surcharge-induced stresses.

IMC—Greenbay

A portion of this impoundment was used in the early 1930's prior to the development of phosphate flotation. During that period, clay fines were generated during mining and washing operations and were subsequently stored with other phosphatic debris in this area. More recently (1960–70) this facility was again used by two other phosphate producers to store clays, this time from flotation debris (minus 150-mesh fines). This demonstrates that storage areas can be rejuvenated and used again after a sufficient consolidation period where solids have stabilized and volumetric capacities are adequate.

Only the southeastern section of this area was sampled since heavy vegetation, which consisted of small trees, shrubs, and native grasses, rendered much of the area inaccessible without destruction of established vegetation. The mean water table for the area was 5 ft below the dam base. An estimated 50% of clay storage is above natural ground level. A "typical" profile of the impounded clays show that yellow-brown to gray clay extends to a depth of 40 ft in certain areas. The upper 10 ft of clays show a well-developed crustal zone which averages 55.2% solids.

DCP soundings also indicate upper zones of highly consolidated clays (fig. A–5), which reflect a well-drained, desiccated surface layer. The mid to bottom hole samples were not as dense as the upper crustal zones. Table 8 shows an average clay column of 44.6% solids. Sand was present but did not occur in appreciable amounts. The TS for the composite sample showed 48.4% solids. No pore pressure readings were taken of this site since liberated pore fluids were not observed.

Table 8.—Data summary of phosphatic clay solids, IMC, Greenbay (GB)

Fraction sampled	C_s	%C	TS
Hole location A:			
Top	55.4	55.1	55.5
Middle	33.2	31.4	36.7
Bottom	45.8	44.1	47.6
Average	44.8	43.5	46.6
Hole location B:			
Top	52.3	52.3	52.4
Middle	43.4	33.9	55.7
Bottom	57.2	37.5	72.0
Average	51.0	41.2	60.0
Hole location C:			
Top	57.0	56.8	57.1
Middle	32.1	31.7	33.1
Bottom	39.6	32.8	50.0
Average	42.9	40.4	46.7
Hole location D:			
Top	56.3	56.2	56.4
Middle	42.3	37.0	49.5
Bottom	32.2	25.8	45.6
Average	43.6	39.7	50.5
Hole location E:			
Top	57.1	57.6	57.7
Middle	37.0	36.8	37.2
Bottom	34.5	33.2	36.9
Average	42.9	42.5	43.9
Hole location F:			
Top	53.0	53.0	53.1
Middle	34.9	34.7	35.2
Bottom	38.8	38.2	39.7
Average	42.2	42.0	42.7
Composite:			
Top	55.2	55.2	55.4
Middle	37.2	34.2	41.2
Bottom	41.4	35.3	48.6
Average	44.6	41.6	48.4

NOTE.—C_s = solids content of clay, %;
%C = clay in slurry, %;
TS = total solids in slurry, %.

IMC—Clear Springs (CS–2)

This area was used to characterize a small (92-acre) impoundment with an above-ground-level storage capacity of approximately 50%. Detailed filling rates are unavailable; however, filling was completed in 1969. Settling depths ranged from 20 to 30 ft because of the previously mined bottom. The estimated water table was 20 ft below the base of the dam which consequently offered a more favorable system for bottom drainage. At depths greater than 10 ft below the surface pore pressure values shown in figure 8 indicate that the existing system has approached a state of equilibrium with the hydrostatic pressure.

After filling in 1969, the area was drained of surface waters and covered with a surcharge of tailing sands. Further sand layers were applied in 1977–78 until a depth of 5 to 9 ft was reached.

Figure A–6 shows horizons of dense clays and sand lenses which are interspersed with the stored clay mass.

An examination of the composite sample data in table 9 indicates that the average top, middle, and bottom fractions of the clay column were consistently high (42.2% to 43.2% solids). Sand was present with many of the clay solids examined, which accounts for the average 52.4% total solids content. Sand tailings were pumped onto the surface of the prethickened clays for the purpose of capping; however, this sand seems to have been inadvertently mixed with the clay as mud-waving occurred.

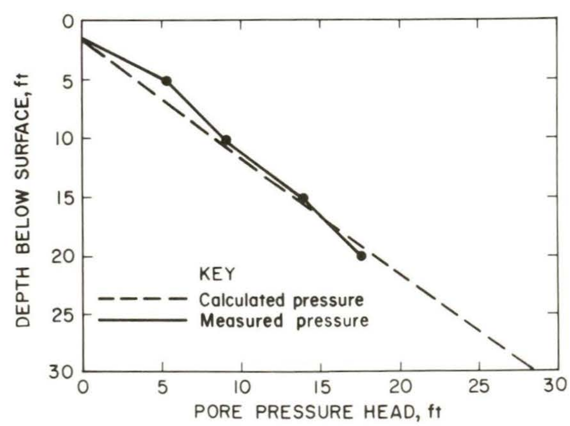


FIGURE 8.—Pore pressure measurements versus hole depth, IMC, Clear Springs (CS–2).

Swift-Mobil—Fort Meade Varn (V)

This area comprises approximately 160 acres of stored clay ranging in depth from 18 to 26 ft where neither sand cap nor mixtures of sand and clay were used. To the north of this impoundment lies a sand tailings storage area of water-saturated sands. In 1962 an extension was constructed around the southern extremity of this impound-

Table 9.—Data summary of phosphatic clay solids, IMC, Clear Springs (CS–2)

Fraction sampled	C_s	%C	TS
Hole location A:			
Top	38.6	28.0	55.4
Middle	34.7	21.4	59.8
Bottom	45.9	29.7	65.0
Average	39.7	26.4	60.1
Hole location B:			
Top	40.1	32.3	43.4
Middle	40.7	39.2	42.8
Bottom	42.8	38.9	47.9
Average	41.2	36.8	44.7
Hole location C:			
Top	55.5	42.3	66.1
Middle	46.3	43.0	50.2
Bottom	48.7	42.7	55.0
Average	50.2	42.7	57.1
Hole location D:			
Top	44.2	41.8	47.3
Middle	40.4	39.5	41.9
Bottom	43.2	40.1	47.3
Average	42.6	40.5	45.5
Hole location E:			
Top	42.9	36.6	51.3
Middle	48.0	38.5	58.2
Bottom	44.2	41.7	47.3
Average	45.0	38.9	52.3
Hole location F:			
Top	32.2	25.7	45.7
Middle	49.9	33.5	66.4
Bottom	34.5	25.3	52.0
Average	38.9	28.2	54.7
Composite:			
Top	42.2	34.4	51.5
Middle	43.3	35.9	53.2
Bottom	43.2	36.4	52.4
Average	42.9	35.6	52.4

NOTE.—C_s = solids content of clay, %;
%C = clay in slurry, %;
TS = total solids in slurry, %.

Table 10.—Data summary of phosphatic clay solids, Swift-Mobil, Fort Meade Varn (V)

Fraction sampled	C_s	%C	TS
Hole location A:			
Top	39.2	39.2	39.2
Middle	37.1	37.1	37.1
Bottom	43.2	43.2	43.2
Average	39.8	39.8	39.8
Hole location B:			
Top	40.9	40.9	40.9
Middle	42.5	40.0	46.0
Bottom	46.9	42.2	52.2
Average	43.4	41.0	46.4
Hole location C:			
Top	55.6	55.6	55.6
Middle	53.4	51.9	54.7
Bottom	55.4	50.6	59.2
Average	54.8	52.7	56.5
Hole location D:			
Top	34.3	34.3	34.3
Middle	39.2	39.2	39.2
Bottom	47.6	43.2	52.5
Average	40.4	38.9	42.0
Hole location E:			
Top	33.4	33.4	33.4
Middle	37.1	37.1	37.1
Bottom	45.0	45.0	45.0
Average	38.5	38.5	38.5
Hole location F:			
Top	34.8	34.8	34.8
Middle	32.9	32.9	32.9
Bottom	42.9	42.9	42.9
Average	36.9	36.9	36.9
Composite:			
Top	39.7	39.7	39.7
Middle	40.4	39.7	41.2
Bottom	46.8	44.5	49.2
Average	42.3	41.3	43.4

NOTE.—C_s = solids content of clay, %;
%C = clay in slurry, %;
TS = total solids in slurry, %.

ment and used to store overflow clays. Hence, two sides of this impoundment were adjacent to water-bearing storage sites.

Field notes of this area indicate a poorly drained surface area, heavily vegetated with small willows and cattail growth. Data from the DCP soundings indicate lenses of dense clay, which is verified in figure A–7.

In table 10 an average clay column shows 39.7% solids near the top, increasing with depth to 46.8% near the bottom. Small amounts of sand or washer debris were noted in the bottom clays, which may have been the result of sizing and/or beneficiation operations.

Pore pressure data shown in figure 9 indicate that the pore fluids pressures are higher than hydrostatic pressures. This seems to indicate that additional drainage is possible before reaching final equilibrium.

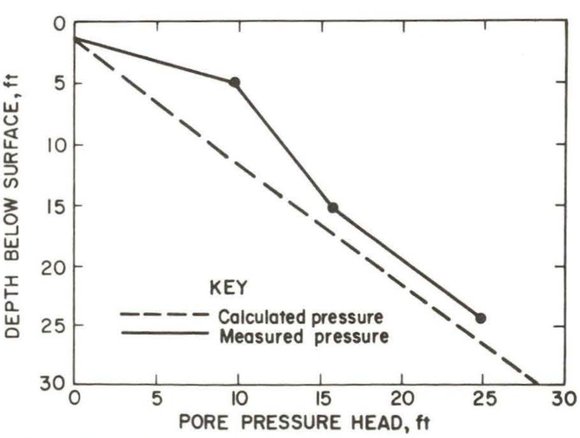


FIGURE 9.—Pore pressure measurements versus hole depth, Swift-Mobil, Fort Meade Varn (V).

Mobil—Homeland (HO–2, HO–3)

These impoundment areas reflect the results of clays stored in above-natural-ground-level impoundments (HO–2) as opposed to clays stored partly above and partly below natural ground level (HO–3).

The first impoundment in this series (HO–2) was used for clay disposal from 1949 through 1960 and had 100% of its storage capacity aboveground. Tailings sands had been pumped onto the surface to form a cap 1 to 4 ft thick. Field notes indicated that approximately 60% of the impoundment perimeter was capped. The entire area was overgrown with grasses, shrubs, and trees, some of which reached 15 ft in height. The interior surface areas of this impoundment had 2 to 5 ft of standing water, which contained aquatic vegetation.

A review of the field notes shows a shallow perched water zone above the sand-clay mixture. The exact cause of the standing water is uncertain; however, the accumulation of rainwater in conjunction with liberated slurry water could be responsible. Generally, the weight of a superimposed sand cap is sufficient to liberate large quantities of secondary slurry water, which collects within interior depressions. Once water collects in these perched-clay basins, it becomes difficult for it to migrate downward through the consolidated clays. Below this horizon and near the bottom, the clays showed good drainage as characterized by the plot in figure 10 of measured pore pressures and DCP (fig. A–8), which show sand accumulation near the bottom. Pore pressures in this

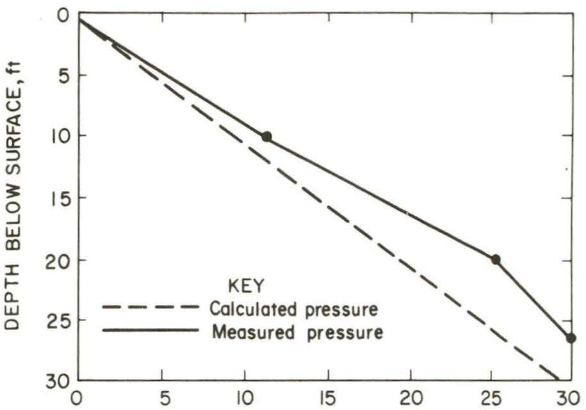


FIGURE 10.—Pore pressure measurements versus hole depth, Mobil, Homeland (HO–2).

Table 11.—Data summary of phosphatic clay solids, Mobil, Homeland (HO–2)

Fraction sampled	C_s	%C	TS
Hole location A:			
Top	39.1	39.0	52.2
Middle	39.2	39.2	39.2
Bottom	40.7	40.7	40.7
Average	39.7	39.6	44.0
Hole location B:			
Top	50.8	37.7	63.4
Middle	39.0	36.1	43.4
Bottom	48.2	48.2	48.2
Average	46.0	40.7	51.7
Hole location C:			
Top	56.0	39.7	68.8
Middle	39.5	39.5	39.5
Bottom	43.8	43.8	43.8
Average	46.4	41.0	50.7
Hole location D:			
Top	37.5	29.8	50.4
Middle	46.1	46.1	46.1
Bottom	47.1	45.3	49.2
Average	43.6	40.4	48.6
Hole location E:			
Top	45.0	34.8	57.5
Middle	49.1	42.4	56.0
Bottom	47.6	46.2	49.2
Average	47.2	41.1	54.2
Hole location F:			
Top	47.0	36.6	58.7
Middle	40.8	38.7	43.8
Bottom	46.1	45.0	47.3
Average	44.6	40.1	49.9
Composite:			
Top	45.9	36.3	58.5
Middle	42.3	40.4	44.7
Bottom	45.6	44.9	46.4
Average	44.6	40.5	49.9

NOTE.—C_s = solids content of clay, %;
%C = clay in slurry, %;
TS = solids content of clay, %;

zone were substantially lower than hydrostatic pressures, indicating dewatering has become almost imperceptible.

Sampling data in table 11 show that the top and bottom portions of an average clay column were 45.9% and 45.6%, respectively. The average value for the entire clay column was 44.6% solids by weight.

The second impoundment (HO–3) had 50% of its storage capacity below ground and was used from 1950 through 1966. At this site, half the area was reclaimed to pasture and had 0 to 8 in of standing water. The remaining half was covered with approximately 1 ft of topsoil and was overgrown with small shrubs and trees 5 to 14 ft tall.

DCP soundings (fig. A–9) show that a thickened clay layer extended from 5 to 20 ft below the surface of the clay. The clays extended to 55 ft at several points sampled. Data in table 12 show that an average clay column contained 36.4% solids at the top and increased to 39.7% solids near the bottom. The average solids content for the entire column was 36.0%. Very little sand was observed in samples examined in the laboratory.

The pore pressure data shown in figure 11 show that pore fluids had not dissipated completely since these values were higher than hydrostatic pressures.

Table 12.—Data summary of phosphatic clay solids, Mobil, Homeland (HO–3)

Fraction sampled	C_s	%C	TS
Hole location A:			
Top	37.5	37.5	40.4
Middle	35.9	36.3	36.8
Bottom	45.0	45.0	45.2
Average	39.5	39.9	40.8
Hole location B:			
Top	37.0	37.1	37.3
Middle	33.1	33.1	33.1
Bottom	27.5	34.2	55.0
Average	32.5	34.8	41.8
Hole location C:			
Top	39.3	39.5	39.9
Middle	34.2	34.3	34.4
Bottom	40.2	41.6	46.8
Average	37.9	38.5	40.4
Hole location D:			
Top	36.6	36.9	37.5
Middle	33.1	33.2	33.3
Bottom	43.1	43.2	43.3
Average	37.6	37.8	38.0
Hole location E:			
Top	31.8	31.8	31.9
Middle	28.8	28.9	29.0
Bottom	41.8	41.8	41.9
Average	34.1	34.2	34.3
Hole location F:			
Top	36.1	36.1	36.1
Middle	26.0	26.0	26.0
Bottom	40.7	40.7	40.7
Average	34.3	34.3	34.3
Composite:			
Top	36.4	36.6	37.2
Middle	31.8	32.0	32.1
Bottom	39.7	41.1	45.5
Average	36.0	36.6	38.3

NOTE.—C_s = solids content of clay, %;
%C = clay in slurry, %;
TS = total solids in slurry, %.

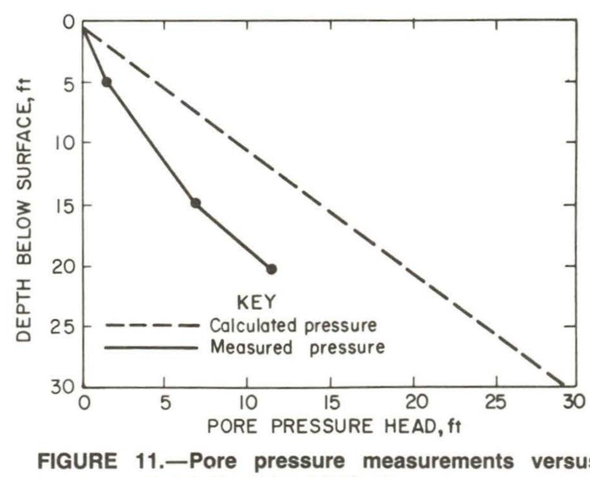


FIGURE 11.—Pore pressure measurements versus hole depth, Mobil, Homeland (HO–3).

IMC—Noralyn (N–2)

This impoundment was designed for 15,000 acre-ft of storage and is 30% above natural ground level. The facility was used from 1952 through 1964 and was filled at the rate of 400,000 to 700,000 tons per year. The fill depths in some areas ranged from 12 to 15 ft, which was less than half the overall design depth. Depths exceeded 40 ft in other areas where mine cuts were used. The ambient water table in this area is estimated at 20 ft below the base of the dam. Access to the sampling area was difficult because of the steep embankments and heavy vegetation within the impoundment area. Laboratory samples revealed small roots and other organic matter with moderate quantities of sand. Tailings sands were deposited along the east and west embankments and along some intersecting dikes.

Data in table 13 show an average of 39.6% total solids for the area. This includes sand, clay, and trace amounts of organics. A typical clay column, less the sand, averaged 36.9% solids. The upper crustal zone shows 39.1% solids. Some interior areas contained 0 to 1 ft of water, which probably reflected recent rainfall.

The pore pressure data in figure 12 indicate that the pore fluid pressures were above hydrostatic pressure. This could result in further potential for drainage. DCP soundings shown in figure A–10 indicate increased clay solids with depth. A dense clay layer is also shown near the bottom interface of the impoundment.

Table 13.—Data summary of phosphatic clay solids, IMC, Noralyn (N–2)

Fraction sampled	C_s	%C	TS
Hole location A:			
Top	41.5	32.2	54.6
Middle	54.0	48.6	58.6
Bottom	25.9	20.9	40.0
Average	40.5	33.9	51.1
Hole location B:			
Top	32.2	29.9	37.0
Middle	31.8	30.9	33.9
Bottom	35.3	34.6	36.7
Average	33.1	31.8	35.9
Hole location C:			
Top	42.9	42.5	43.4
Middle	35.3	35.0	35.8
Bottom	28.8	28.2	30.2
Average	35.7	35.2	36.5
Hole location D:			
Top	32.0	31.0	34.1
Middle	34.3	34.1	34.6
Bottom	33.9	33.8	34.1
Average	33.4	33.0	34.3
Hole location E:			
Top	40.5	40.0	41.2
Middle	39.9	39.4	40.5
Bottom	35.1	35.0	35.3
Average	38.5	38.1	39.0
Hole location F:			
Top	45.3	44.4	46.5
Middle	37.3	37.2	37.4
Bottom	38.5	38.4	38.6
Average	40.4	40.0	40.8
Composite:			
Top	39.1	36.7	42.8
Middle	38.8	37.5	40.1
Bottom	32.9	31.8	35.8
Average	36.9	35.3	39.6

NOTE.—C_s = solids content of clay, %;
%C = clay in slurry, %;
TS = total solids in slurry, %.

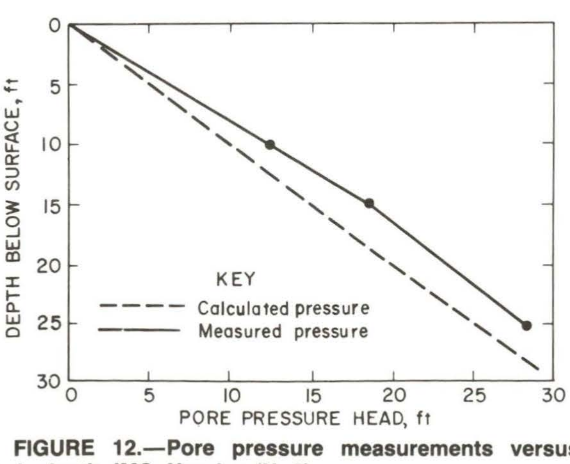


FIGURE 12.—Pore pressure measurements versus hole depth, IMC, Noralyn (N–2).

Agrico—Carmachael Property (Pit 9)

This impoundment represents the oldest (1945) settling area examined in this study. The original impoundment covered 175 acres and was constructed in 1940. Clay filling was begun in 1941 and was completed in 1945. A portion of this area has been reclaimed and returned to private ownership as a domestic pasture. The remaining area is overgrown with thick vegetative cover, vines, native shrubs, and trees. Access to parts of the area was difficult because of steep slopes and gully erosion. This area had been mined and reclaimed prior to the enactment of mandatory reclamation standards.

In 1976 sample data by the company indicated that the consolidated clays had reached an average 39.9% solids. Recent (1982) sampling by the Bureau (table 14) showed an average 43.1% clay solids. These data indicate that only a 3.2% increase in solids content has occurred during the last 15 yr. Some sand was found in the samples, which raised the average total solids content to 56.2%.

Field logs in figure A–11 indicate that gray clay mixed with small amounts of sand extends to an average depth of 24 ft. DCP soundings were not available in this site because of the massive vegetation and the irregular topography, which would require unnecessary environmental disturbance to the stability of the area. The local water table is approximately 6 ft below the base of the impoundment.

Table 14.—Data summary of phosphatic clay solids, Agrico, Carmachael Property (pit 9)

Fraction sampled	C_s	%C	TS
Hole location A:			
Top	40.6	39.8	41.8
Middle	23.6	13.4	56.8
Bottom	71.2	60.5	75.6
Average	45.1	37.9	58.1
Hole location B:			
Top	31.2	27.8	38.7
Middle	42.5	42.5	42.5
Bottom	44.8	38.2	52.9
Average	39.5	36.2	44.7
Hole location C:			
Top	17.6	14.5	39.1
Middle	47.6	44.7	50.8
Bottom	38.2	37.4	39.5
Average	34.5	32.2	43.1
Hole location D:			
Top	58.4	37.1	73.6
Middle	49.0	17.7	81.6
Bottom	51.8	19.7	81.7
Average	53.1	24.8	79.0
Composite:			
Top	37.0	29.8	48.3
Middle	40.7	29.6	57.9
Bottom	51.5	39.0	62.4
Average	43.1	32.8	56.2

NOTE.—C_s = solids content of clay, %;
%C = clay in slurry, %;
TS = total solids in slurry, %.

Agrico—Boyette (B–1, B–2, B–5)

The following three sites represent impoundments that were stage-filled continuously to design capacity before the input was diverted to another impoundment. Filling of the initial site was begun in 1949 and completed in 1954. This impoundment included 300 acres and was constructed almost entirely above natural ground level. No sand cap or clay-sand mixture was used in filling this site. However, sand was found in the samples along the periphery. After filling, most initial surface water was drained and the exposed clay surface was allowed to desiccate. Field data indicated a 2-ft crustal development.

DCP soundings and core logs indicate that gray clays extended to an average depth of 18 ft. Data in figure A–12 show that a well-consolidated clay mass exists throughout an average vertical profile. A dense bottom layer clay averaging 43.0% solids was obtained from sample data from impoundment B–1, as shown in table 15. This dense zone seems to indicate good bottom drainage and dissipation of pore water pressures. The total solids content for an average columnar profile was 61.8%.

The second impoundment (B–2) was divided into portions in which the bottom appeared to be both above and below natural ground level. Several soundings were taken before identifying this condition. In some areas the total depth reached 20 ft, while in others it extended to 30 ft. Consequently, an average profile for this area was difficult to ascertain. Table 16 shows that a columnar profile contained 42.2% clays by weight with traces of sand. Figure A–13 shows thickened clays to a depth of 20 ft.

Table 15.—Data summary of phosphatic clay solids, Agrico, Boyette (B–1)

Fraction sampled	C_s	%C	TS
Hole location A:			
Top	53.2	50.2	55.8
Middle	53.5	47.6	58.6
Bottom	50.6	39.4	61.5
Average	52.4	45.7	58.6
Hole location B:			
Top	49.5	44.9	54.3
Middle	44.6	24.9	69.1
Bottom	70.0	25.8	77.0
Average	54.7	31.9	66.8
Hole location C:			
Top	ND	ND	72.1
Middle	44.9	22.3	72.6
Bottom	53.8	41.0	64.8
Average	49.4	31.6	69.8
Hole location D:			
Top	54.9	51.3	57.9
Middle	39.2	39.2	39.2
Bottom	5.1	3.6	33.7
Average	33.1	31.4	43.6
Hole location E:			
Top	55.0	50.6	58.6
Middle	45.1	37.7	54.2
Bottom	42.5	31.9	56.8
Average	47.5	40.1	56.5
Hole location F:			
Top	20.4	6.0	76.5
Middle	29.7	10.4	75.3
Bottom	36.2	14.2	75.0
Average	28.8	10.2	75.6
Composite:			
Top	46.6	40.6	62.5
Middle	42.8	30.4	61.5
Bottom	43.0	26.0	61.5
Average	44.1	31.8	61.8

NOTE.—C_s = solids content of clay, %;
%C = clay in slurry, %;
TS = total solids in slurry, %.

Table 16.—Data summary of phosphatic clay solids, Agrico, Boyette (B–2)

Fraction sampled	C_s	%C	TS
Hole location A:			
Top	22.0	22.0	75.0
Middle	52.2	52.2	54.4
Bottom	43.8	43.7	46.7
Average	39.3	39.3	58.7
Hole location B:			
Top	41.6	41.6	41.6
Middle	37.5	37.5	37.5
Bottom	36.9	36.9	36.9
Average	38.7	38.7	38.7
Hole location C:			
Top	54.1	54.1	54.1
Middle	38.9	38.9	38.9
Bottom	42.8	42.8	42.8
Average	45.3	45.3	45.3
Hole location D:			
Top	50.9	50.9	50.9
Middle	38.0	38.0	38.0
Bottom	42.7	42.7	42.7
Average	43.9	43.9	43.9
Hole location E:			
Top	50.9	50.9	50.9
Middle	40.5	40.5	40.5
Bottom	40.5	40.5	40.5
Average	44.0	44.0	44.0
Composite:			
Top	43.9	43.9	54.5
Middle	41.4	41.4	41.9
Bottom	41.3	41.3	41.9
Average	42.2	42.2	46.1

NOTE.—C_s = solids content of clay, %;
%C = clay in slurry, %;
TS = total solids in slurry, %.

The third impoundment (B–5) was identified as a flow-through impoundment. In flow-through impoundments clay solids are introduced on one side of the impoundment, while liberated surface waters are discharged at the other extremity. Drainage weirs are adjusted to pass only clear water while retaining the clay solids in the impoundment. Surface water is continuously displaced by input clay slurry; hence total retention and clay settling time are governed by a volumetric balance. As a result, a gradient is usually produced as heavier, larger particles settle near the inlet while the finer sized, lighter particles are deposited near the discharge. This condition is not always evident where multiple input-output arrangements are used or where small (less than 200 acres) "square" impoundments are used.

In this impoundment 300 acres were used to retain an estimated 5,000 acre-ft of clay solids. Filling of this area was begun in 1961 and completed in 1965. A major portion of this impoundment was extensively reclaimed and is covered with nearly impenetrable vegetation. Figure A–14 shows core logs of the fill area, which had an undulating bottom; the logs reflect varying levels of clay. Sample data in table 17 show a well-developed upper clay layer averaging 47.0% solids; the columnar profile average was 46.2% overall solids. No DCP soundings were available at this site. Figure 13 shows that between 5 and 10 ft an abrupt decrease in pore pressures was recorded.

Table 17.—Data summary of phosphatic clay solids, Agrico, Boyette (B–5)

Fraction sampled	C_s	%C	TS
Hole location A:			
Top	38.1	32.2	46.0
Middle	44.4	24.3	69.5
Bottom	35.4	21.2	61.4
Average	39.3	26.2	59.0
Hole location B:			
Top	30.4	20.7	52.6
Middle	22.2	11.5	59.7
Bottom	41.3	19.0	73.0
Average	31.3	17.1	61.8
Hole location C:			
Top	59.8	30.1	79.8
Middle	63.9	40.3	77.2
Bottom	54.2	28.7	75.8
Average	59.3	33.0	77.6
Hole location D:			
Top	55.6	26.2	79.1
Middle	52.1	29.6	72.8
Bottom	56.6	38.5	70.5
Average	54.8	31.4	74.1
Hole location E:			
Top	51.0	23.2	77.7
Middle	48.4	29.3	68.8
Bottom	40.2	22.9	66.0
Average	46.5	25.1	70.8
Composite:			
Top	47.0	26.7	67.0
Middle	46.2	27.0	69.6
Bottom	45.5	26.1	69.3
Average	46.2	26.6	68.6

NOTE.—C_s = solids content of clay, %;
%C = clay in slurry, %;
TS = total solids in slurry, %.

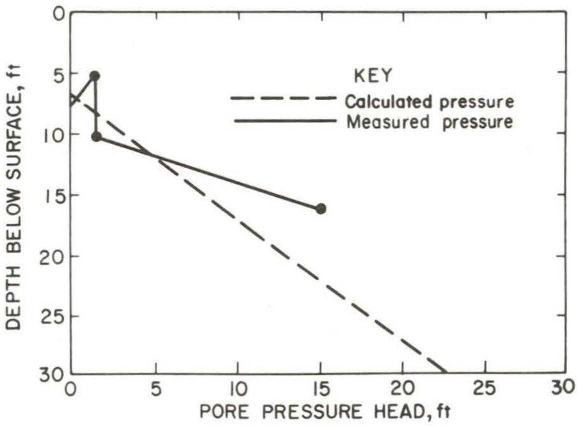


FIGURE 13.—Pore pressure measurements versus hole depth, Agrico, Boyette (B–5).

GENERAL SUMMARY—CONVENTIONAL DISPOSAL PROCESS

In summarizing the data obtained from this study, several general observations can be made to characterize the overall state of conventional settling and consolidation of phosphatic clay. A collective plot (fig. 14*A*) of the clay solids content from all impoundments studied versus the elapsed settling and consolidation time shows that the percent solids of impounded clay reaches a maximum in 20 to 25 yr of natural settling. Not surprisingly, these clays settle most rapidly during the initial 3 to 30 months, in which the largest volume of liberated water is drained and returned to the process system. After this initial period, some system of external stresses must be applied to cause subsequent consolidation of the solids to the point that crustal structure will develop and support capping

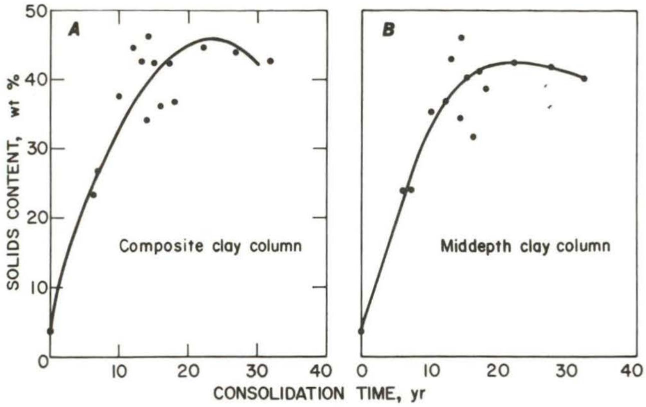


FIGURE 14.—Clay solids versus consolidation time.

with sand tailings and/or overburden. This surcharge of material is necessary to exert vertical stresses on the underlying clays to squeeze the remaining interstitial water from the pore spaces.

A better representation of the solids data is shown in figure 14*B*, where the middepth averages of the clay column are plotted. By using the middle portion of the clay column, the average clay content is not influenced by solids from the highly variable crustal zone; hence the plotted data improved from a 71.6% to a 92% confidence level in plotting a least-squares distribution.

After 20 yr of consolidation and with assistance from the sand cap, the clay solids in conventional impoundments could reach an upper limit of approximately 45%. At this stage, consolidation slows considerably. Phosphate researchers have reported (*1*, p. 5) that most clays in the

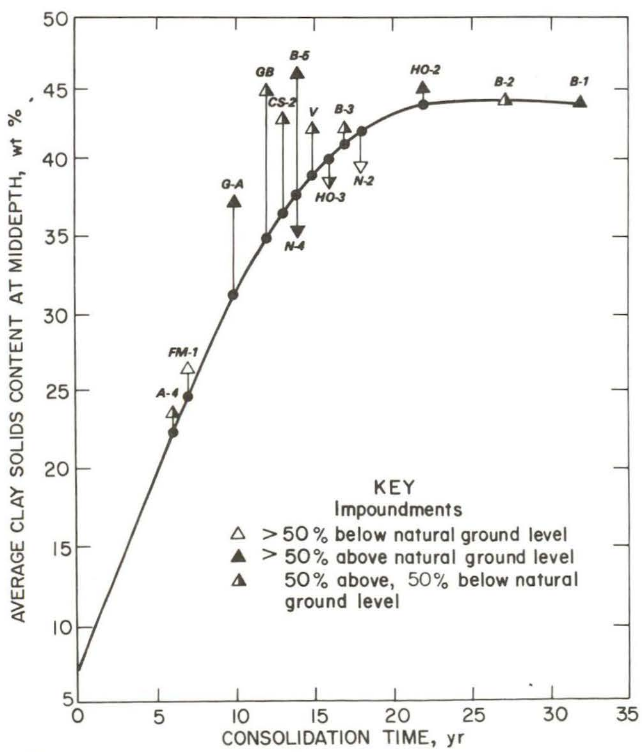


FIGURE 15.—Above-ground-level impoundments versus below-ground-level impoundments.

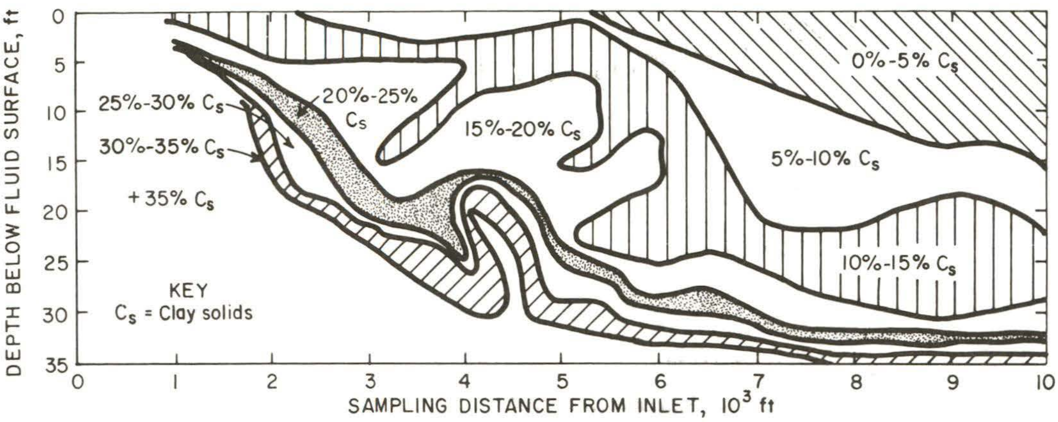


FIGURE 16.—Profile of AMAX impoundment BF–1 settling area.

phosphate matrix average only 60% solids in the "natural" (premined) state. Consequently, the clay solids content eventually should approach this upper limit as a result of conventional consolidation.

The data in figure 14*B* are replotted in figure 15 with the actual percentage of clay solids from each test site plotted at the extension of the arrow. In this manner, the direction of the arrow illustrates the deviation in solids content above or below the base curve. For example, arrow B–5 shows that this site is 10 percentage points higher in clay solids than the projected base curve for 14 yr of natural settling. Sites represented by solid triangles are impoundments with >50% of their storage capacity above natural ground (ANG) level. Impoundments represented by half-open triangles are partly above and partly below ground level (i.e., storage in or near existing water table). Data show that sites B–5, G–A, and HO–2, which are >50% ANG, do in fact exceed projected clay solids content. Data provided by other researchers (AMAX, Inc.) but not shown in figure 15 indicate that another ANG impoundment (BF–1) reached 35% solids within months near the input side of the impoundment. These data and company information suggest further studies are needed to support these preliminary findings which show that ANG-level impoundments or impoundments with artificially lowered water tables tend to drain better than below-natural-ground-level systems.

Another significant point regarding conventional settling techniques involves basic impoundment design (geometry) and its relationship to fixed-position slurry inlets. As an example, AMAX, Inc., in October 1977 began filling a 522-acre impoundment (BF–1) with a designed capacity of 13,000 acre/ft of clay storage. This impoundment was constructed on unmined land and was unique in that it was 1,000 ft wide, 30 ft deep, and 4 miles (≈21,000 ft) long. The inlet slurry was introduced at the southeast corner of the impoundment and was induced to flow northward along the greater dimension. A total of 55 clay samples were obtained by Bromwell Engineering, Inc. (*9*) from points along an east-west line at 9 sample stations which advanced northward from the southern inlet. Clay solids were determined at these points, and the data were plotted on an isogram as shown in figure 16.

Preliminary results indicated that clay solids established a gradient of decreasing solids with flow from the fixed inlet. A vertical profile of the downstream flow showed the clay solids increased with depth from an upper clay zone of 0% to 5% solids to 35% solids at bottom. Figure 16 also shows that the greater volume of 35% plus clay solids occurred near an inlet (within 1,000 ft). Additional data are being collected by Bromwell Engineering, Inc., to determine particle size and plasticity index values on the consolidated clays with reference to downstream sample stations.

DEVELOPED AND EXPERIMENTAL ALTERNATIVES TO CONVENTIONAL DISPOSAL

As a result of basic experimentation, several techniques were proposed to replace or augment conventional clay disposal technology. However, to date, no system has completely replaced conventional disposal because of the voluminous amount of clay slurry requiring treatment. A distinction should be made at this point between using prethickened clay via conventional methods of consolidation and prethickening of clays by in-line processes.

The sand-spraying and the dredge-mix processes utilize prethickened clays derived from conventional settling areas. These prethickened solids are subsequently treated with sand tailings as the basis for final, in-place reclamation. Conversely, the in-line processes such as the Gardinier, Enviro-Clear, and rotary screen utilize flocculants to initially prethicken the clay solids. Regardless of the process used to prethicken the clays, the ultimate goal is stabilization and reclamation of all clay solids while returning the impoundment areas to a useful state at or near the original contour. Often a slightly elevated or diked area is preferred, to compensate for any future subsidence and for drainage of surface water from the area.

SAND-SPRAYING PROCESS

One of the earliest efforts to improve the state-of-the-art technology of phosphatic clay reclamation was the

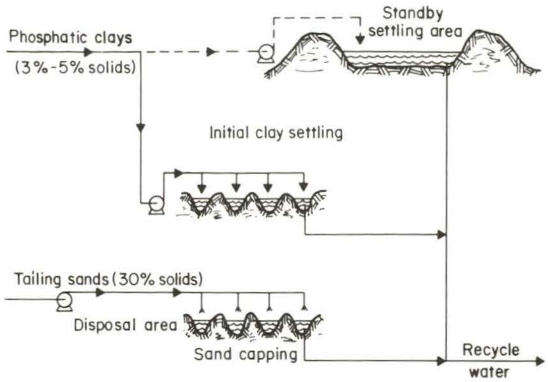


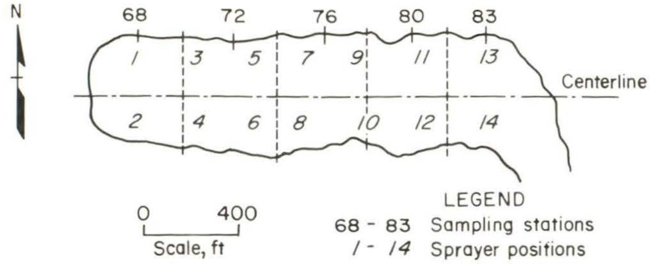
FIGURE 17.—Brewster's sand-spraying process.

sand-spraying technique pioneered and developed by Brewster Phosphates, Inc. This technique was one of the first full-scale, commercial applications utilizing tailings sands as a vehicle for consolidating and reclaiming clay areas. Several researchers had visualized using tailings sands to promote clay settling via reagentized coating of the sand particles, induced self-weight of surcharged sand cap, and sand layer filtration. However, Brewster's sand-spraying technique was unique in that it was designed to create a uniform sand-clay mixture in place, which would serve as a basis for rapid reclamation of mined lands. Figure 17 illustrates the conceptual sand-clay spraying process.

In this process, clays prethickened to 12% to 15% solids were subsequently sprayed with sand at predetermined time intervals. The spray units were strategically placed in an effort to evenly distribute the sand on the prethickened clay surface (crust). After spraying, the sand particles were allowed to descend through the prethickened mass until equilibrium was reached. The timing of the sand spray cycle was dependent on the developed clay structure to "fix" the position of the sand particle within the clay mass. Often the falling sand particles created channels to the surface where liberated slurry water could flow. In practice, this allowed the clay mass to densify as the water was displaced by the thickened clays. Generally, repeated applications of sand were necessary to optimize the total structural integrity of the mixture.

In March 1975, a large-scale test was conducted at Brewster's Haynsworth Mine to evaluate the effects of spraying prethickened phosphatic clays with tailings sands. For this test, a series of parallel mine cuts 350 ft wide, 30 to 40 ft deep, and 2,000 ft long were arranged in a serpentine configuration with earthen baffles to train the flow of clays. The clays exited the beneficiation plant at 3.5% solids and at a nominal rate of 34,000 gal/min. Once in place, the clays were allowed to settle naturally to approximately 13% solids, then sprayed with sand at a rate of 825 ton/h via a floating pipeline using specially adapted spray nozzles. Adjacent cuts were subsequently filled with raw clays, and the process was repeated. Fifteen cuts covering approximately 550 acres were dedicated to this experiment.

Excerpts from a 1975 progress report by the Florida Phosphatic Clays Research Project (FPCRP) show the results of a sampling program used to evaluate the effectiveness of this early test. Figure 18 shows a plan view of zone A and the positions of the sand sprayer and the location of the sampling stations. The sprayers were



Calculation of sand-clay ratio (S/C) and change in solids content (minus 150-mesh basis)

Zone	Solids before	Clay	Sand	Solids after	S/C	ΔS
A-68	14.5	1.05	3.20	19.4	3.03	4.9
72	13.8	1.91	3.00	17.3	1.57	3.5
76	16.9	1.85	3.04	19.6	1.65	2.7
80	12.3	1.35	2.70	19.0	2.00	6.7
83	12.8	.98	1.75	ND	1.78	ND
Composite	14.1	NAp	NAp	18.8	2.01	NAp
B-68	12.8	.94	3.65	ND	3.88	ND
72	11.7	.94	3.32	19.9	3.54	8.2
76	13.1	1.32	3.20	19.3	2.42	6.2
80	12.5	1.05	3.08	19.8	2.94	7.3
83	12.8	1.17	1.88	20.5	1.60	7.7
Composite	12.6	NAp	NAp	19.9	2.88	NAp

NAp Not applicable. ND Not determined.
Source: Bromwell, L. E. Progress Report on Brewster Sand Spraying Experiment. FL Phosphate Clays Res. Project, Oct. 1975, pp. 1-53

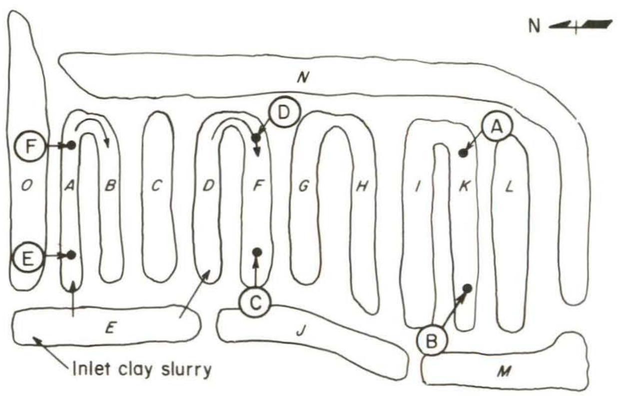
FIGURE 18.—Sprayer positions and coring data from sand-spraying area.

periodically moved from west to east along the filled area as indicated. Data tabulated below the plan indicate that the clays in zone A (stations 68–83) averaged 14.1% solids before the first spraying on June 11, 1975. A second spraying was applied to the same area approximately 2½ months later, and subsequent sampling data showed an average increase of 4.7% clay solids. Zone B data (fig. 19) indicate that the clays averaged 12.6% clay solids before spraying and increased to 19.9% solids after spraying. The data also show that the sand-to-clay ratios averaged 2.01 in zone A and 2.88 in zone B.

An updated progress report for January-June 1976 published by the FPCRP shows that the composite of zones A, B, D, and F averaged 25.6% clay solids in March 1976 and increased to 26.8% clay solids in June.

In August 1982, the Bureau of Mines conducted an intensive core testing program at the Haynsworth Mine near the original test site. Although the exact sampling stations could not be determined, the same area of investigation was established. In figure 19 the original test zones are identified by capital letters *A–O*. The Bureau's sampling stations are identified by circled letters which generally coincide with zones A and B. As represented, sample locations Ⓔ and Ⓕ are located generally in the original zones A and B, which have been subsequently reclaimed. Stations Ⓒ and Ⓓ correspond to zone F, and stations Ⓐ and Ⓑ correspond to zone K.

A sampling suite composed of six randomized locations is shown in table 18. The composite average of these samples shows that the consolidated clays average 32.6% solids for the columnar profile. The sand-to-clay ratio averaged 8.4 (S/C) for the areas sampled. The increased sand content of the clay is attributed to the placement of the sand cap used in final reclamation of the area. Samples obtained at D and E showed upper clay solids of 40.4% and 47.4% solids. Total solids, composed of sand and clays, average 78.4%. Field observations indicated that solids contents of this magnitude could easily support the weight of light farm equipment used for agricultural purposes.



Hole fraction	F			D			A		
	C_s	S/C	TS	C_s	S/C	TS	C_s	S/C	TS
Top	28.0	5.7	85.2	40.4	11.6	82.9	23.9	10.9	78.8
Middle	29.2	6.8	83.5	46.9	13.5	84.7	32.3	5.7	76.2
Bottom	29.6	7.0	83.3	44.6	23.2	71.1	24.9	3.0	57.2
Composite	28.9	6.5	84.0	44.0	16.1	79.6	27.0	6.5	70.7
Hole fraction	E			C			B		
	C_s	S/C	TS	C_s	S/C	TS	C_s	S/C	TS
Top	47.4	2.3	74.7	22.9	6.4	78.6	23.0	10.9	78.0
Middle	47.4	4.4	82.9	15.2	3.5	80.2	17.7	10.9	72.3
Bottom	45.6	4.4	82.2	44.4	16.5	79.3	24.2	12.2	80.5
Composite	46.8	3.7	79.9	27.5	8.8	79.4	21.6	11.3	76.9

C_s = Percent solids (clay only); S/C = sand-clay ratio; TS = total solids (sand-clay).

FIGURE 19.—Correlation of 1975 versus 1982 sand-spraying data.

Table 18.—Data summary of phosphatic clay solids, Brewster, Haynsworth (H–1)

Fraction sampled	C_s	%C	S/C	TS
Hole location A:				
Top	23.9	6.7	10.9	78.8
Middle	32.3	11.4	5.7	76.2
Bottom	24.9	14.2	3.0	57.2
Average	27.0	10.8	6.5	70.7
Hole location B:				
Top	23.0	6.6	10.9	78.0
Middle	17.7	6.0	10.9	72.3
Bottom	24.2	6.2	12.2	80.5
Average	21.6	6.3	11.3	76.9
Hole location C:				
Top	22.9	6.4	11.5	78.6
Middle	15.2	3.5	21.3	80.2
Bottom	44.4	16.5	3.8	79.3
Average	27.5	8.8	12.2	79.4
Hole location D:				
Top	40.4	11.6	6.2	82.9
Middle	46.9	13.5	5.2	84.7
Bottom	44.6	23.2	2.1	71.1
Average	44.0	16.1	4.5	79.6
Hole location E:				
Top	47.4	22.8	2.3	74.7
Middle	47.4	15.4	4.4	82.9
Bottom	45.6	15.4	4.4	82.2
Average	46.8	17.9	3.7	79.9
Hole location F:				
Top	28.0	5.7	13.8	85.2
Middle	29.2	6.8	11.5	83.5
Bottom	29.6	7.0	10.8	83.3
Average	28.9	6.5	12.0	84.0
Composite:				
Top	30.9	10.0	9.3	79.7
Middle	31.4	9.4	9.8	80.8
Bottom	35.6	13.8	6.0	75.6
Average	32.6	11.1	8.4	78.4

NOTE.—C_s = solids content of clay, %; S/C = sand-clay ratio; %C = clay in slurry, %; TS = total solids in slurry,%.

The percentage of clay (C_s) obtained from the composite sample suite indicated that the clay solids averaged 11.1% (by weight) where the total slurry contained sand, clay, and interstitial water.

Core logs and DCP soundings indicate that the final sand cap for this area ranges from 5 to 18 ft in thickness. Sand lenses and sand-clay mixtures were interspersed within the clay body, which extended to a depth of 40 to 50 ft.

Standing water was observed in some areas that could be attributed to the release of secondary pore water and/or rainfall events. The overall stability of the area was excellent except for a few depressed areas. It is reasonable to assume that some subsidence will continue as redistribution of stresses occurs within the clay structure (fabric).

A second test area was used that was adjacent to the original test site at Haynsworth Mine. This site covered approximately 80 acres and was used to test and improve the sand distribution system for the sand-spraying technique. Access to the area was good with the exception of drainage ditches which bisected the area. Surface drainage is necessary to remove excess water from the clay surface to increase bearing strengths prior to sand application. DCP soundings used to select sample stations were erratic because of the fluctuating depth of the sand cap.

Data summarized in table 19 show that the clay surface had a well-developed crust which averaged 41.0% clay solids. The sand-to-clay ratio for this area averaged 5.2 (S/C) and contained an average of 74.4% total solids (clay plus sand). The columnar average of the clays from this area was 36.0% solids. However, because of the 5.2 S/C mixture, the total percentage of clay (C_s) in the slurry system averaged 15.4. Consequently, 5.2 times the weight of sand was used per clay unit.

A third series of sand-spraying tests was conducted at the Lonesome Mine in July 1978. At this site modifications were again made in the sand-spraying equipment to improve the sand distribution system. Relocation of the transfer lines and fixed spray nozzles required continuous

Table 19.—Data summary of phosphatic clay solids, Brewster, Haynsworth (H–2)

Fraction sampled	C_s	%C	S/C	TS
Hole location A:				
Top	43.0	18.8	3.0	75.0
Middle	24.9	8.7	7.3	73.3
Bottom	23.1	8.5	7.4	71.7
Average	30.3	12.0	5.9	73.3
Hole location B:				
Top	63.6	20.3	3.4	88.4
Middle	41.5	15.2	4.1	78.5
Bottom	21.9	7.8	8.3	71.7
Average	42.3	14.4	5.3	79.7
Hole location C:				
Top	34.0	16.0	3.3	68.9
Middle	38.3	16.1	3.6	74.0
Bottom	31.3	9.4	7.5	79.4
Average	34.5	13.8	4.8	74.1
Hole location D:				
Top	46.4	23.6	2.1	72.7
Middle	51.9	41.5	.5	61.6
Bottom	43.3	31.3	.9	59.2
Average	47.2	32.1	1.2	64.5
Hole location E:				
Top	27.5	8.2	8.5	78.3
Middle	25.4	7.2	10.1	78.9
Bottom	26.1	10.2	6.0	71.1
Average	26.3	8.5	8.2	76.1
Hole location F:				
Top	31.4	9.7	7.1	78.8
Middle	37.6	12.1	5.6	79.9
Bottom	37.1	12.9	5.0	78.0
Average	35.4	11.6	5.9	78.9
Composite:				
Top	41.0	16.1	4.6	77.0
Middle	36.6	16.8	5.2	74.4
Bottom	30.5	13.3	5.9	71.9
Average	36.0	15.4	5.2	74.4

NOTE.—C_s = solids content of clay, %; S/C = sand-clay ratio; %C = clay in slurry, %; TS = total solids in slurry, %.

monitoring to prevent sand loading of an area and created a labor-intensive problem. At one period, a sand slinger was used to propel the sand in a fashion similar to that of a lawn water sprinkler. Abrasive action and wear were factors leading to discontinuing its use.

A DCP trace of this area shows a sand-overburden cap 5 to 10 ft thick, which served as a substrate for vegetation. Below this cap, light brown to gray clays contained lenses of sand and thickened sand-clay mixtures. DCP soundings indicate that the clay-sand mixture was not uniformly distributed but contained zones of high sand concentrations, which is indicated by low-valued DCP traces. Sample station L–1 shows alternating spikes in zones with well-developed sand-clay mixtures (fig. A–17).

Table 20.—Data summary of phosphatic clay solids, Brewster, Lonesome (L–1)

Fraction sampled	C_s	%C	S/C	TS
Hole location A:				
Top	23.4	6.5	11.1	78.7
Middle	38.4	5.6	.8	53.3
Bottom	33.2	10.6	6.4	78.8
Average	31.7	7.6	6.1	70.3
Hole location B:				
Top	52.0	34.0	1.0	68.6
Middle	27.2	8.0	8.8	78.6
Bottom	21.6	12.0	3.7	56.6
Average	33.6	18.0	4.5	67.9
Hole location C:				
Top	44.9	11.7	6.3	75.2
Middle	48.9	39.4	.5	58.8
Bottom	51.5	43.8	.3	58.8
Average	48.4	31.6	2.4	64.3
Hole location D:				
Top	33.1	10.5	6.4	78.7
Middle	42.9	19.1	2.9	74.6
Bottom	46.6	32.0	1.0	63.4
Average	40.9	20.5	3.4	72.2
Hole location E:				
Top	27.5	10.5	7.8	76.9
Middle	26.8	19.7	7.8	76.2
Bottom	37.9	34.6	2.5	68.5
Average	30.7	21.6	6.0	73.9
Hole location F:				
Top	14.5	6.9	10.4	78.3
Middle	24.0	6.9	10.4	78.2
Bottom	35.2	19.8	2.2	63.4
Average	24.6	11.2	7.7	73.3
Hole location G:				
Top	42.9	19.8	2.7	73.5
Middle	40.8	25.4	1.5	63.1
Bottom	44.9	23.0	2.1	71.8
Average	42.9	22.7	2.1	69.5
Hole location H:				
Top	25.2	9.5	6.6	71.9
Middle	27.7	9.2	7.2	75.9
Bottom	25.6	8.3	8.1	75.8
Average	26.2	9.0	7.3	74.5
Hole location I:				
Top	27.4	11.4	5.8	77.3
Middle	34.2	11.5	5.5	74.9
Bottom	32.1	11.3	5.7	76.0
Average	31.2	11.4	5.7	76.5
Hole location J:				
Top	32.7	9.6	7.3	80.2
Middle	69.8	17.7	4.2	77.2
Bottom	40.6	15.4	4.0	77.9
Average	47.7	14.2	5.2	78.4
Hole location K:				
Top	50.5	34.8	.9	65.9
Middle	39.1	18.4	2.9	71.2
Bottom	34.8	14.1	4.2	73.6
Average	41.5	22.4	2.7	70.2
Hole location L:				
Top	27.0	10.4	5.9	71.8
Middle	29.8	11.5	5.3	72.8
Bottom	39.2	14.3	5.4	77.8
Average	32.0	12.1	5.5	74.1
Composite:				
Top	33.4	14.6	6.0	74.8
Middle	37.5	16.0	4.8	71.2
Bottom	36.9	19.9	3.8	70.2
Average	36.0	16.8	4.9	72.1

NOTE.—C_s = solids content of clay, %; %C = clay in slurry, %; S/C = sand-clay ratio; TS = total solids in slurry, %.

Table 20, which consists of data from 12 sample stations, indicates an average clay solids content of 36.0%. The average sand-to-clay ratio decreased to 4.9 (S/C), which was improved over previous tests. The average total solids for this area was 72.1%, which included both sand and clay components.

Table 21 shows the results of a composite sample obtained from a site adjacent to L–1. At this site the clay content averaged 29.2% solids, and the average sand-clay ratio was 8.2 The total solids, consisting of both sand and clay, was 75%.

Pore pressure measurements, plotted in figure 20, show that the sand-clay mixture had the potential for further dewatering of the solids as the pore pressures were higher than hydrostatic pressures. Field notes indicate approximately 1 ft of water appeared in depressed areas where unconsolidated materials surfaced. DCP sounding (fig. A–18) showed interspersed zones of sand and clay.

Table 21.—Data summary of phosphatic clay solids, Brewster, Lonesome (L–2)

Fraction sampled	C_s	%C	S/C	TS
Hole location A:				
Top	21.3	5.9	12.3	78.2
Middle	26.5	9.2	7.1	74.4
Bottom	23.7	10.2	5.5	67.0
Average	23.8	8.4	8.3	73.2
Hole location B:				
Top	29.5	14.4	3.5	65.6
Middle	33.1	11.7	5.6	76.4
Bottom	25.2	11.9	4.5	64.9
Average	29.3	12.7	4.5	69.0
Hole location C:				
Top	25.5	5.6	13.9	83.6
Middle	28.7	6.9	10.8	82.7
Bottom	27.9	6.8	10.9	82.3
Average	27.4	6.4	11.9	82.9
Hole location D:				
Top	18.1	3.5	22.4	84.0
Middle	48.0	31.3	1.1	66.0
Bottom	49.9	21.4	2.7	78.6
Average	38.7	18.7	8.7	76.2
Hole location E:				
Top	21.6	6.3	11.0	77.0
Middle	21.2	8.6	6.8	68.0
Bottom	37.1	13.8	4.5	76.5
Average	26.6	9.6	7.4	73.8
Composite:				
Top	23.2	7.1	12.6	77.7
Middle	31.5	13.5	6.3	73.5
Bottom	32.8	12.8	5.6	73.9
Average	29.2	11.1	8.2	75.0

NOTE.—C_s = solids content of clay, %; %C = clay in slurry, %; S/C = sand-clay ratio; TS = total solids in slurry, %.

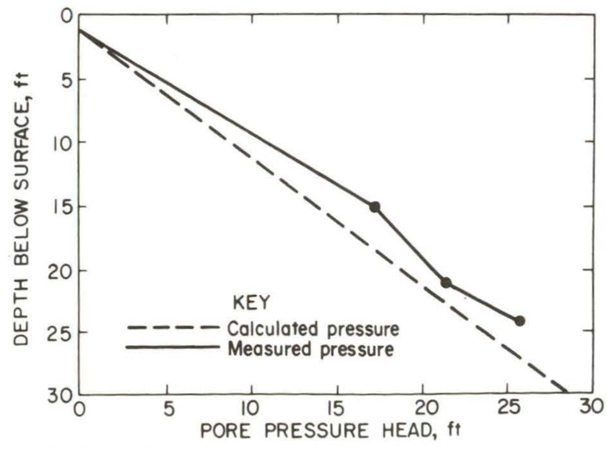


FIGURE 20.—Pore pressure measurements versus hole depth, Brewster, Lonesome (L–1).

Table 22.—Summary of Brewster sand-spraying technique for phosphatic clay disposal and/or reclamation

Mine location	C_s	%C	S/C	TS
Haynsworth:				
H–1	32.6	11.1	8.4	78.4
H–2	36.0	15.4	5.2	74.4
Lonesome:				
L–1	36.0	16.8	4.9	72.1
L–2	29.2	11.1	8.2	75.0
Composite .... av. pct.	33.4	13.6	6.7	75.0

NOTE.—C_s = solids content of clay, %; %C = clay in slurry, %; S/C = sand-clay ratio; TS = total solids in slurry, %.

The sand-spraying process is an alternative to conventional phosphatic clay disposal where site-specific conditions, clay content, and mineralogy are favorable. This process has been used effectively at two mines to reclaim land and to produce a stable heterogeneous sand-clay mixture capable of supporting pasture and other light agricultural uses. Under this set of site-specific conditions the composite clays consolidated to 33.4% solids within 2 to 5 yr. The composite sand-clay ratio of 6.7 indicates 6.7 times the weight of sand was mixed with a unit weight of clay. The combined total solids content of the mixture was 75%, with clay solids occupying 13.6% of the slurry by weight (table 22).

Several factors cause the sand-spraying process to be attractive:

1. Rapid (2–5 yr) rate of achieving reclamation.
2. Stability of the sand-clay fill.
3. Simultaneous disposal of sand and clay plant materials.
4. Low-profile final dikes.
5. Relative cost effectiveness as compared to other systems.

To date, Brewster Phosphates, Inc., has committed more than 2,000 acres to the sand-spraying reclamation process. Central Farmers, Inc. (CF) is also conducting sand-spraying reclamation. Lands reclaimed and revegetated by this process have generally met the stringent reclamation standards imposed by State and Federal regulatory agencies. Field demonstrations have shown that these areas will support most indigenous plant and animal species and provide aesthetically acceptable landforms.

Although the sand-spraying process may offer an alternative to conventional clay disposal, its use must be tempered with considerations for site-specific conditions. Namely, there are considerable differences between reclaiming lands at a mature mine as opposed to reclaiming waste clay disposal at a new mine. In a mature mine, the existing mine cuts are such that with proper shaping, additional capacity could be developed for alternative storage. Alternative storage must be available to handle the current flow of slurry during the prethickening stage of the spray process. In addition, stored sand tailings from previous operations may be necessary for optimizing sand-clay admixtures and to complete the fill heights for final restoration of the sand-spraying area. Currently, the sand-to-clay ratio in processed matrix is not sufficient to sustain continuous reclamation without an additional source of sand tailings. The sand-spraying reclamation process utilizes only 40% of the plant's clay waste; conventional settling areas are still required to store the remaining 60% of the phosphatic clays generated at a mine.

At a new mine, large-capacity impoundments must be constructed initially, to accommodate the total flow of processed slurry while providing storage for the prethickening clay cycle of the sand-spraying process. Also, optimum prethickening of clays could require the use of shallow impoundments covering large surface areas.

Among the factors to be considered before adopting the sand-spraying disposal process are—

1. Rapidity required for restoration of the land.
2. Availability of sufficient sand tailings for a material balance.
3. Availability of initial clay storage and/or sand stockpile.
4. Location of the final disposal site relative to the beneficiation plant.
5. Intended land use for the reclaimed site.

Other factors, not readily apparent, may seem equally important; namely, the timely restoration of environmentally sensitive areas, land in heavily populated residential areas, and wetland ecosystems.

DREDGE-MIX PROCESS

The dredge-mix process demonstrates another technique of utilizing sand tailings as a vehicle for reclaiming clay-settling areas. In this process, researchers at IMC have shown that prethickened clays (≈ 18% solids) could be dredged from initial clay-settling areas, pumped to mixing sites, and blended with sand tailings for final disposal in the mine cuts. The significance of this process is that no commercial flocculant is required to agglomerate the initial clay mass. IMC has completed extensive studies (*1*, pp. 60–83) designed to standardize procedures for routinely pumping high-clay solids (≈18% solids), which are critical to the overall succes of the dredge-mix process. Details of the dredge-mix process are illustrated in figure 21. Preliminary results from earlier tests indicated that the sand-clay mix resulted in 74% total solids and contained clays of 21% solids. An 8-ft cap of tailing sands was subsequently used to enhance further consolidation of the sand-clay mixture. In this demonstration some segregation of the sand-clay mixture was observed, which seems a condition inherent in most sand-clay mixtures.

Another variation of the dredge-mix process was demonstrated by Swift and Co. (now Estech, Inc.), which employed an in-line mixing process in which raw clays were treated with a suitable flocculant and mixed with sand for in-common-line disposal. Results produced during

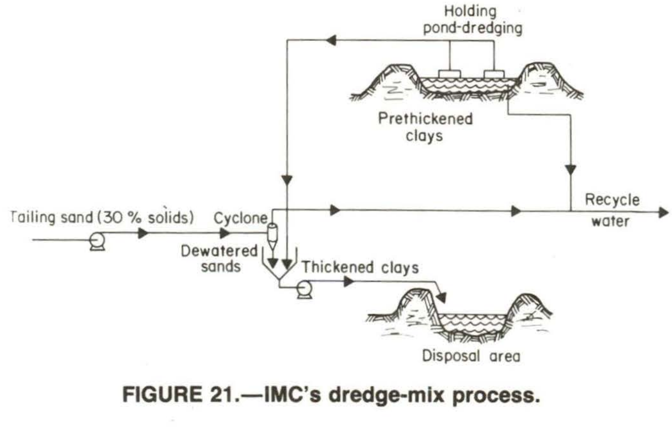


FIGURE 21.—IMC's dredge-mix process.

this demonstration showed an average clay solids content of 25.9% However, significant separation of sand and clay was noted. Additional studies to improve this process involved modification of the in-line mixing unit and selection of flocculants with high shear strengths to prevent broken clay-sand bonds.

FLOCCULATED SYSTEMS

The use of flocculants for initial sedimentation of phosphatic clays was proposed in early 1972 at the time of the establishment of a cooperative agreement between the USBM and FPCRP. Since 1972, hundreds of flocculating agents have been screened and tested for suitable application in treating up to 80,000 gal/min of raw plant clays. Flocculation costs and the residual effects on future beneficiation processes have greatly reduced the number of available flocculants. However, certain proprietary flocculants have been developed for use on a commercial scale to handle these voluminous slurries.

Gardinier Process

The Gardinier process evolved from independent studies conducted by researchers of Gardinier, Inc. Preliminary tests showed that a two-stage flocculating system using proprietary flocculants was required to effectively achieve the reported 27% to 32% clay solids. A complete process diagram is shown in figure 22, which describes the basic material flow. In this process, plant slurry at 3% to 5% solids is introduced to a surge tank and is subsequently metered and blended with flocculants in the Clariflux thickener. The Clariflux thickener offers a unique system in which newly injected feed pulp flows through a previously bedded pulp. Clarified water is decanted from the upper zone of the thickener, while the agglomerated solids are collected at the bottom and pumped to a secondary flocculation stage. In this secondary stage, sand tailings are added to form a sand-clay admixture. The solids resulting from this two-stage flocculation process are subsequently pumped to specially prepared mine cuts for continued settling and consolidation. This proposed system will be incorporated into the main clay discharge line at Gardinier, Inc., to process the entire plant volume. A scaled-up production model has been constructed and is undergoing tests. Future plans propose using five commercial-size units to handle the total clay discharge of the Fort Meade plant. Gardinier, Inc., has committed approximately $20 million to fully develop this commercial venture.

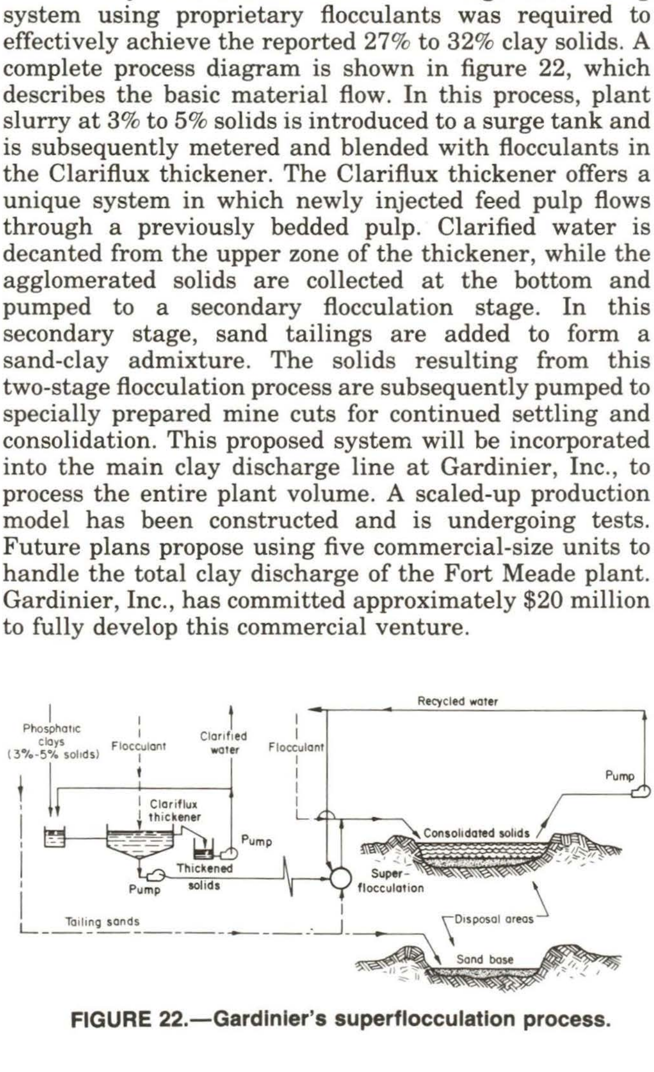


FIGURE 22.—Gardinier's superflocculation process.

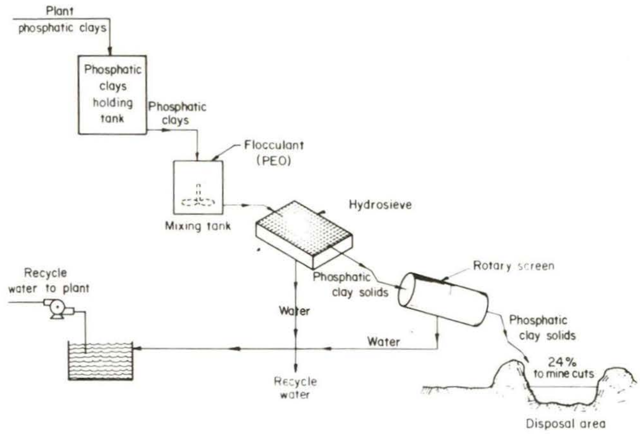


FIGURE 23.—Bureau of Mines' rotary screen process.

Rotary Screen Process

The Bureau of Mines is developing an in-line dewatering technique for phosphatic clay that uses a flocculating reagent, polyethylene oxide (PEO) (*10*). This flocculant forms strong stable flocs, which can be partially dewatered on a static screen and further dewatered on a rotary screen, in a matter of minutes. Using this technique, illustrated in figure 23, a field test unit (FTU) was operated at Estech Chemical Co.'s Silver City Mine and Occidental Chemical Co.'s Suwannee River Mine. Consolidated phosphatic clay material containing up to 24% clay solids was produced when feed slurries of 3% to 5% clay solids were treated. Pit tests indicate that products containing greater than 30% clay solids can be achieved in several months. The technique is not dependent on sand or overburden materials to achieve a high initial solids content. Thus, since the phosphatic clays are not diluted, the potential for future recovery of their contained values is promising.

One of the most significant advantages to this process is the in-line ability of rapid at-the-plant dewatering and the tenacious ability of the dewatered solids not to reslurry. Another advantage is that individual process units can be operated either in tandem or independently. The Bureau is currently operating a prototype unit to be used in a cooperative effort with Agrico Chemical Co.'s Fort Green Mine in Polk County. The unit will provide engineering data that can be used to design a commercial in-line system.

Enviro-Clear Process

The Enviro-Clear process is an in-line system that employs a combination of flocculant and sand tailings for the consolidation and final disposition of clay solids. This process emphasizes the ability to incorporate a commercial thickener into a system to initially dewater plant clays to such a consistency that a sand-clay mixture can be formed. The system was initially field-tested in October 1981 by Estech, Inc., and has since been scaled to near production capacity of the Watson Mine at Fort Meade, FL. The flocculant used to treat the in-line clay slurry is a proprietary anionic polymer which is injected into a sand-clay premixing tank prior to entering the Enviro-Clear thickener. The up-flow system of introducing this mixture into the thickener is the unique feature of this

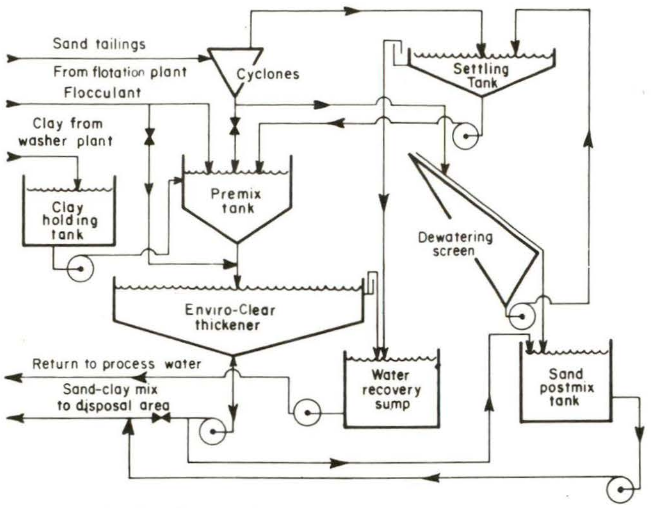


FIGURE 24.—Estech's Enviro-Clear process.

process. Figure 24 shows the complete process flow, which produces clarified water and a sand-clay admixture for direct deposition into prepared mine cuts.

The Gardinier, rotary screen, and Enviro-Clear processes all use flocculants to initially consolidate the clays; hence, each is uniquely effective on a specific suite of clay minerals. Although sand tailings are used in conjunction with the Gardinier and Enviro-Clear processes, the manner in which the clay solids are treated and admixed with sand determines the effectiveness of the system. Consequently, each plant facility must formulate its site-specific disposal system, which may require final treatment at the reclamation site.

CONSOLIDOMETER TESTS—A CLAY SLURRY EVALUATION TECHNIQUE

A major concern in the disposal of phosphatic clays is the difficulty of accurately predicting the settling and consolidation characteristics of phosphatic clays so as to effectively incorporate these data into the design of clay disposal structures. In the past, the design of settling impoundment depended largely on rule-of-thumb methods and/or the experience of the individual designer. However, since the enactment of Florida's 1975 environmental laws, more detailed planning is required to address the problems of environmental impact of disposal sites, budgeted water supplies, and general reclamation standards than in the past. Construction standards also were set by the Department of Environmental Regulation that reflect more stringent design criteria for impoundment structures in an effort to avert the possibility of dike failures. Consequently, the ability to adequately forecast storage requirements and to optimize impoundment geometries could translate into a substantial savings of both energy and financial resources.

Early efforts to optimize impoundment designs required laboratory determinations such as the Atterburg limits, clay-settling tests, and charting electrochemical activity of the clay slurries among many other variable properties used for first-approximation calculations. While these are fundamentally important engineering properties for classical geotechnical investigations, they do not directly address the variability of mineral compositions and the void ratios and permeabilities of the clay slurries with respect to time. Also, impoundment filling rates, initial percent solids, and particle size of the clays are important considerations required in design work.

A general equation[7] for calculating filling height is expressed as

$$h = aQ^bt^c,$$

where h = height of sediment (m),
Q = filling rate of dry solids ($kN{\cdot}m^2/yr$),
t = filling period (yr),
and a, b, c = empirical coefficients.

The height of filling, h, depends directly on the rate of filling, Q, and the empirical coefficients a, b, and c, which are derived via laboratory tests for a specific clay slurry. Consequently, total height of filling is greatly influenced by the accuracy of these coefficients.

To address these problems, several investigators (*11*) have formulated mathematical models that recognize the importance of combining production data with the variable properties associated with clay slurries. Each clay slurry has a characteristic suite of properties that must be determined in the laboratory. These data are subsequently encoded into computer programs that define boundary conditions and operating parameters required to optimize available clay storage capacities. Once a program is instituted, the computer can simulate changes in operating conditions so that proper adjustments can be made with regard to slurry input rates, projected fill heights, clay dewatering rates, and remaining storage capacity of a particular impoundment. The following programs are available in the literature (*12*) for use with the McDonnell-Douglas Automation Co. DAC 2: FLINSI, FLINDI, FLCOSI, FLCODI, QSNSI, QSUSI, QSNDI, QSUDI.

The FL programs address the densification of phosphatic clay slurries during initial filling of the impoundment. The QS programs evaluate the conditions of clay slurries during quiescent consolidation over given intervals of time. The letters "S" and "D" in the program titles denote a system with either single (S) or double (D) drainage boundary conditions. Numerical analysis of these systems can be used to examine older sites or to evaluate new alternative methods of phosphatic clay disposal. Often older disposal sites that have subsided can

[7] Carrier, W. D., III, L. G. Bromwell, and F. Somogyi. Design Capacity of Slurried Mineral Waste Ponds. J. Geotech. Eng. Div., ASCE, 1981, 53 pp.

be modified to include additional storage capacity. Hence, a method for evaluating the total capacity of the system (previously disposed clays plus "new" clays) can be of extreme importance.

GENERAL SETTLING AND CONSOLIDATION THEORY

The ultimate disposal of phosphatic clays can be divided into three basic stages: (1) the initial settling and sedimentation of clay solids, (2) the compression and consolidation of the clay skeleton, and (3) final capping and reclamation of the clay area.

A complete analysis of the sedimentation and consolidation theory of phosphatic clay slurries is beyond the scope of this report. However, certain conceptual elements are discussed in an effort to reflect the complexity of the phosphatic clay disposal problem.

Industry data indicate that beneficiated clays from phosphatic matrix entrap large volumes of process water, often as much as 30 times its in situ volume. It is this large volume of slurry that must be reduced, consolidated, and finally stored. During the initial impoundment, sedimentation of clays occurs in a dilute environment in which the input slurry ranges from 3% to 5% clay solids. Slurry entering a disposal area generally settles rather quickly under quiescent conditions where solid-to-solid particle density is low. As the slurry densifies, a zone of material (solids plus fluid) develops common settling characteristics that react en masse; i.e., the settling velocity of specific clay particles is fixed relative to velocities of other particles within this zone. Consequently, the total settling depth is composed of a finite set of identifiable layers. These layered zones form the initial stage of sedimentation as discrete particles of clay become agglomerated into groups or flocs, which soon begin to exert compression and self weight on the ambient system. The zone immediately above the settled layer contains clear supernatant fluid (water), which forms a well-defined interface with the settled solids. Below this zone the flocs are compressed into more dense solids which form the basis for consolidation structure. The liberated (supernate) water at this stage of development can be immediately reclaimed and recycled to the beneficiation plant. An estimated 90% of this water can be ultimately recycled at most plant facilities (*13,* p. 63).

The second stage involves further compression and consolidation of the discrete layers or zones of settled solids. As the particle density en masse increases, there is a corresponding decrease in voids between particles and/or agglomerated flocs. This in effect causes a decrease in the permeability of the system by restricting the flow paths of liberated water. The rate of consolidation is governed primarily by the dissipation and ultimate drainage of the pore fluids from within the total clay system. Hence, the drainage of a particular clay system depends on its boundary conditions as related to void ratio, permeability, and the inherent relationship to effective stresses.

CONSTANT RATE OF DEFORMATION TESTING PROCEDURE

The Constant Rate of Deformation Consolidometer (CRDC) Mark II (*14*) is a device developed at the University of Colorado for determining the physical properties of phosphatic clay slurries. Information obtained from the Mark II is input data for resolving one-dimensional finite strain consolidation problems via computer iterations. The total system offers a rapid approach to predicting the behavior of phosphatic clay slurries while simulating field conditions in the laboratory.

In practice, clay slurries are placed in a Teflon-lined metal cylinder and subjected to constant rate of deformation via a loading ram, as illustrated in figure 25. The test cell is equipped with an undrained bottom (except at the pressure transducer port), while the top is fitted with a porous disk and millipore filter paper to allow only the fluid portion of the sample to drain. A constant back pressure is applied to the upper boundary of the sample and is closely regulated by a system of hydraulic and pneumatic controls. Total stress transducers and a pore pressure transducer measure and record the output on a strip chart recorder. The loading ram travels at a constant velocity commensurate with the characteristic nature of the tested sample. Most of the data generated by this system can be obtained after approximately 150 h of testing. This system greatly compresses the time usually required by conventional settling and consolidation methods.

During the initial testing, the void ratio of the sample slurry deforms at a constant velocity as the solid-liquid components redistribute. This relationship causes a change in the void ratio as pore fluids become liberated and the solid-to-solid spacing is decreased. The permeability of the solid-liquid system changes in direct response to the changes in void ratio. This condition influences the rate of dissipation of the pore fluids and ultimately the rate of drainage from the system. As drainage occurs, a new set of boundary conditions is formed which require a series of interactions to adequately describe the system. This stepwise approach is ideally suited for computer applications.

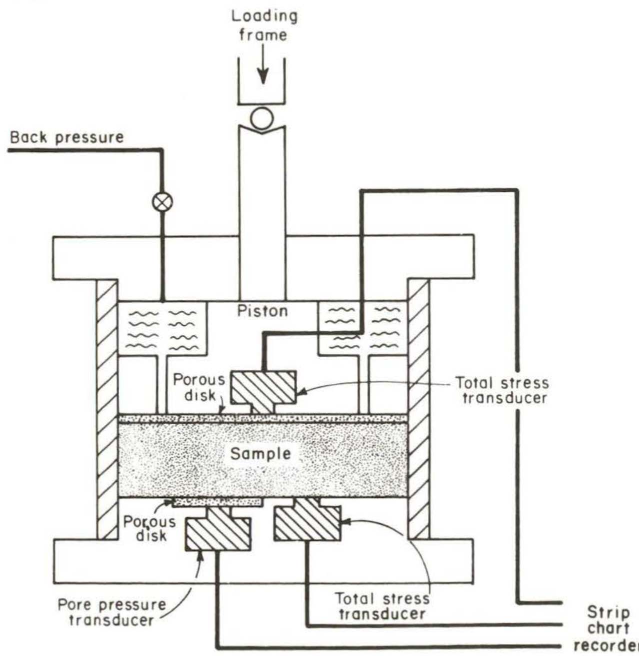


FIGURE 25.—Consolidometer for testing processed phosphatic clays.

LABORATORY RESULTS OF CONSOLIDOMETER TESTS

To illustrate the utility of this system, three phosphatic clay slurries were tested using the CRDC to differentiate between the unique properties of each clay slurry and to evaluate their respective process treatments (disposal systems).

Figures 26–29 summarize the plotted results of consolidometer tests and analyses of three alternative processes to phosphatic clay disposal: (1) The Brewster process involved the use of tailings sands that were sprayed onto the surface of prethickened clays for in-the-cut disposal without the use of commercial flocculants; (2) the Gardinier process used two-stage flocculation to create a sand-clay mixture for below-natural-ground-level disposal; (3) the Bureau of Mines rotary screen process used flocculants only to concentrate the in-line clay slurry without utilizing tailings sands. Figure 26 thus reflects the compressibility of the clay skeleton as it relates the amount of effective stress to the void ratios produced during a specific time increment on the raw unprocessed samples that subsequently were used for the rotary screen and superflocculation processes. (Samples of the raw untreated material used for the sand-spray process were not available.) Figure 27 illustrates the permeability of these samples as a function of the void ratio, which subsequently translates into rate of pore fluid dissipation and ultimately the densification of the solids.

Comparing the untreated (raw plant clays) shown in figures 26 and 27 with the process-treated clays shown in figures 28 and 29 at a common void ratio of 5, the following process characteristics are notable:

- Brewster sand-clay process
  1. Highest effective stress value (31 kN/m^2) of group tested.
  2. Permeability of 9×10^{-8} m/s.
- Gardinier process
  1. Lowest effective stress value (7 kN/m^2) when treated (flocculated).
  2. Effective stress in flocculated state is about the same as in raw state.
  3. Only nominal increase in permeability of the flocculated material as opposed to permeability of untreated material.
- Bureau of Mines rotary screen process
  1. Effective stress less for flocculated as opposed to unflocculated raw material.
  2. Total permeability not appreciably different in the flocculated as opposed to the unflocculated materials.

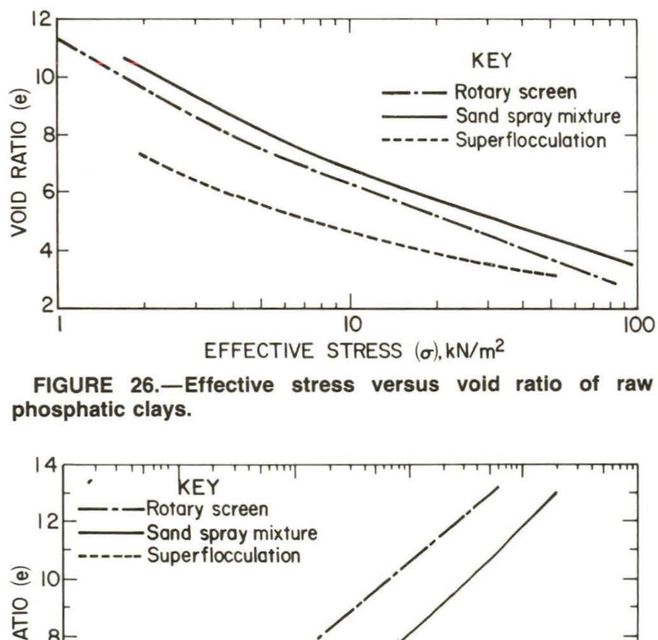


FIGURE 26.—Effective stress versus void ratio of raw phosphatic clays.

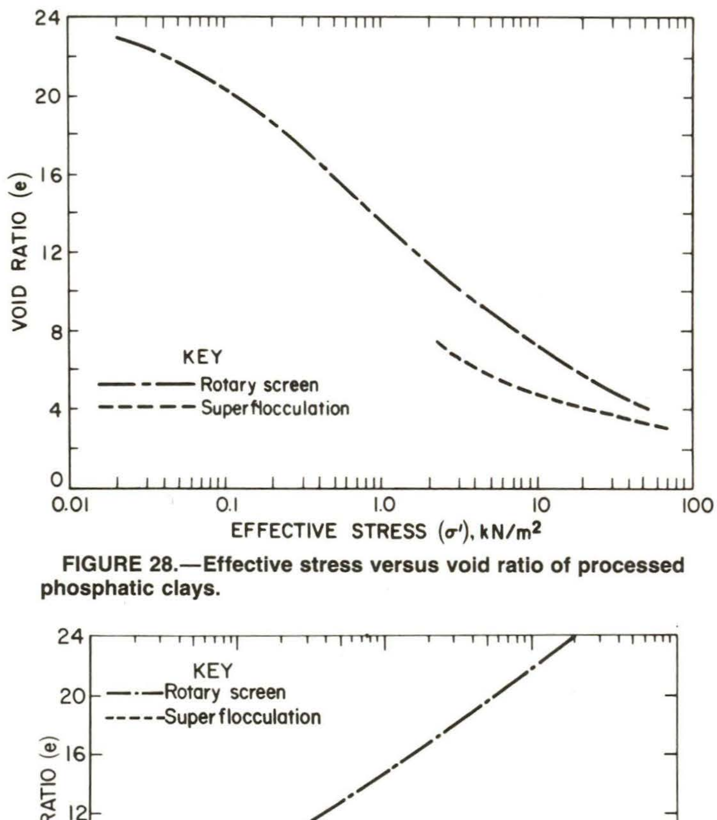


FIGURE 28.—Effective stress versus void ratio of processed phosphatic clays.

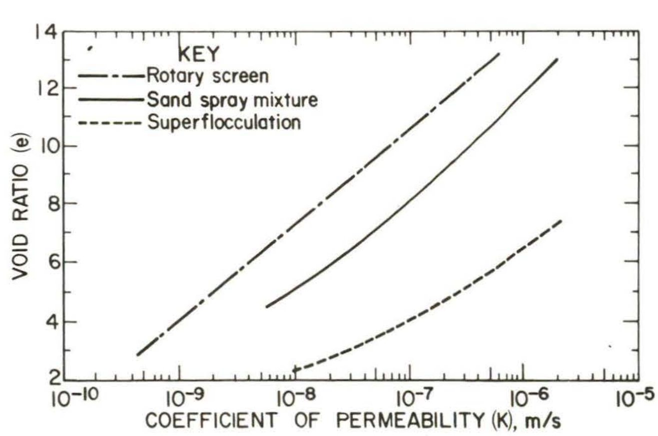


FIGURE 27.—Permeability versus void ratio of raw phosphatic clays.

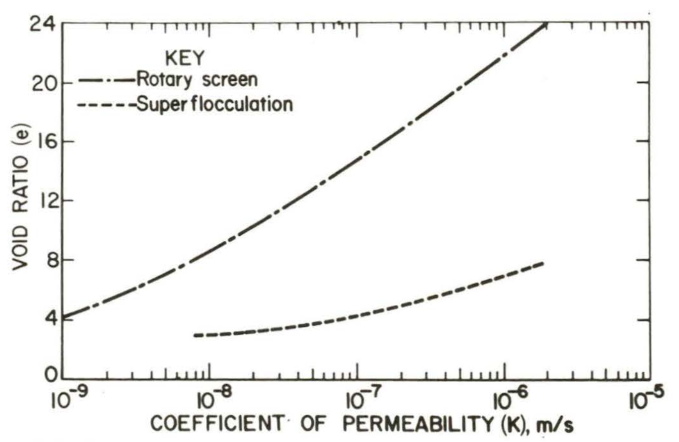


FIGURE 29.—Permeability versus void ratio of processed phosphatic clays.

A comparison of void ratio versus coefficient of permeability of each process shown in figure 29 indicates that the Gardinier clays exhibited a greater range of permeabilities per corresponding void ratio than did the Brewster or Bureau of Mines clays. This was also reflected by the permeability curves, compared in figure 29, of the untreated Gardinier (superflocculation) clays and Bureau of Mines (rotary screen) clays, which seem to infer that the Gardinier clays originally had natural drainage characteristics greater than those of the Bureau clays. Data in figure 28 also indicate that for a given stress of 10 kN/m^2, the sand spray process, rotary screen, and superflocculant processes had void ratios of 7.0, 6.3 and 4.4, respectively. This suggests that the lower void ratios yield closer particle-to-particle spacing and consequently a more densely packaged slurry. Assuming the nonlinear relationship for effective stress to void ratio shown in figure 28, the superflocculant process would achieve the greater terminal solids for the three slurries examined. The greater the terminal percent solids, the more clay solids that ultimately can be stored in a given volume.

In using the family of effective stress, permeability, and void ratio curves, the various clay types and/or proposed clay consolidation systems can be effectively compared and evaluated within a period of hours as opposed to years of conventional testing. This procedure minimizes some of the risks involved in impoundment design.

FINAL RECLAMATION OF CLAY IMPOUNDMENT AREAS

In the past, reclaiming mined-out lands was often considered irrelevant to the planning, mining, and production of mineral deposits. Development and production of minerals nearly always overshadowed reclamation planning. However, this attitude and the resultant adverse publicity prompted the public, environmental groups, and regulatory agencies to declare that ". . . if the land cannot be effectively reclaimed it cannot be mined." This attitude placed the burden of proof on the miners to demonstrate that current reclamation practices and proven technology could effectively restore the land to a useful state.

While final capping with sand tailings and overburden appears to be a standard reclamation procedure for clay disposal areas, the method for uniformly distributing the initial sand cap poses a unique problem for the industry. An extensive effort to resolve this problem has been undertaken collectively by IMC, Agrico, and Mobil. In a special progress report by Dr. J. E. Lawver, (*1*), several approaches were reported that had been tested and documented, as follows:

1. Modifying sand-spray procedures.
2. Tailings side delivery system.
3. Bulldozer operations.
4. Agricultural interface studies.
5. High ratio sand-clay application.
6. Woven fabric interfacing with side delivery methods.

The report emphasized the need for specialized equipment and/or a system that can deliver adequate capping and avoid mud waving.

Research is continuing in an effort to enhance the consolidation of phosphatic clays using conventional impoundments, with special emphasis on well-designed, more efficient monitoring and volumetric control of clay slurries. Management techniques have been developed that encourage computer modeling of production data and the utilization of intrinsic clay properties so as to optimize designed storage capacity while subsequently minimizing total surface disturbance.

CONCLUSIONS

The information developed during this project indicates that conventional impoundments are vital to all new mine developments for initial storage. Conventional impoundments, when designed using best available technology, can be constructed to minimize areal extent by (1) proper placement of inlet-outlet points, (2) initial use of flocculants, (3) surcharge stressing of consolidated clays and/or increasing drainage boundaries (surface and underdrainage), and (4) effective utilization of sand tailings.

Conventional impoundments are necessary to provide—

1. Initial settling areas of clays during mine development.
2. Reservoirs for recirculating plant water.
3. Catch basins for area rainfall and to control surface runoff.
4. Potential for future phosphate resources.

Processes that utilize sand-clay mixtures tend to promote stable land forms that can be adapted to a variety of land uses according to preconceived reclamation plan. Initial planning for these areas is important from the standpoint of materials handling for cost effectiveness.

In-line processing of clays either with or without flocculants serves only to compress the initial time-frame of the sedimentation process. Most of the "in-line" processes reviewed achieve 15% to 28% solids within weeks, depending on the system used and the unique physicochemical properties of the slurry. In each case, initial settling areas are required to allow the pretreated clays reaction time for settling and initial consolidation. These initial holding areas may be in the form of modified mine cuts for in-place restoration or classical impoundments. Realistically, the current in-line processes could translate to a net savings of 1 to 2 yr initially, which suggests that a balanced combination of in-line and conventional systems will conceivably reduce the current time requirements for final reclamation.

REFERENCES

1. Lawver, J. E. Slimes Consolidation and Land Reclamation Study. IMC-Agrico-Mobil, Prog. Rep. 6, 1982, pp. 4–15, 60–83.
2. Sanglerat, G. The Penetrometer and Soil Exploration. Interpretation of Penetration Diagrams—Theory and Practice. Elsevier, 1972, 464 pp.
3. Smelley, A. G., and I. L. Feld. Flocculation Dewatering of Florida Phosphatic Clay Wastes. BuMines RI 8349, 1979, 26 pp.
4. Mitchell, J. K. Fundamentals of Soil Behavior (V. 16, Series in Soil Engineering). Univ. CA—Berkeley, 1976, 422 pp.
5. Bromwell, L. G. Analysis and Prediction of Phosphatic Clay Consolidation. Bromwell Eng., Inc., 1979, 38 pp.
6. Lamont, W. E., J. T. McLendon, L. W. Clements, Jr., and I. L. Feld. Characterization Studies of Florida Phosphate Slimes. BuMines RI 8089, 1975, 38 pp.
7. Bromwell, L. G. Evaluation of Alternative Processes for Disposal of Fine-Grained Waste Materials. Bromwell Eng., Inc., 1982, 23 pp.
8. ———. Dewatering and Stabilization of Waste Clays, Slimes and Sludges (Lecture Series, Soil and Site Improvement). Univ. CA—Berkeley, 1976, 43 pp.
9. Bromwell Engineering, Inc. Physico-Chemical Properties of Florida Phosphatic Clays. FL Inst. Phosphate Res., No. 80–02—003, Dec. 1980, 93 pp.
10. Smelley, A. G., and B. J. Scheiner. Synergism in Polyethylene Oxide Dewatering of Phosphatic Clay Wastes. BuMines RI 8436, 1980, 18 pp.
11. Somogyi, F., B. Keshian, Jr., L. G. Bromwell, and W. Carrier III. Consolidation Behavior of Impounded Slurries. May 1981, 17 pp; available from Bromwell Engineering, Inc., Lakeland, FL.
12. Bromwell Engineering, Inc. Finite-Strain Consolidation User's Manual (FSCON). Oct. 1981, 17 pp.
13. Zellars, M. E., and J. M. Williams. Evaluation of the Phosphate Deposits of Florida Using the Minerals Availability System (contract JO 377000, Zellars-Williams, Inc.). BuMines OFR 112–78, 1978, 199 pp.; NTIS PB 286 648/AS.
14. Znidarcic, D., and R. Schiffman. Constant Rate of Deformation Consolidation Testing. Univ. CO, Dep. Civil, Environ., and Architectural Eng., Feb. 1982, 20 pp.

APPENDIX.—PENETROMETER SOUNDINGS AND CORE LOGS

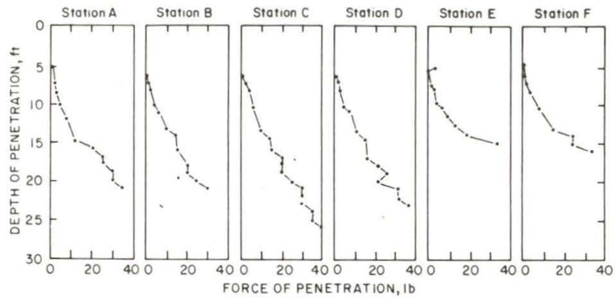


FIGURE A-1.—Hand-driven penetrometer soundings, IMC, Achan (A-4).

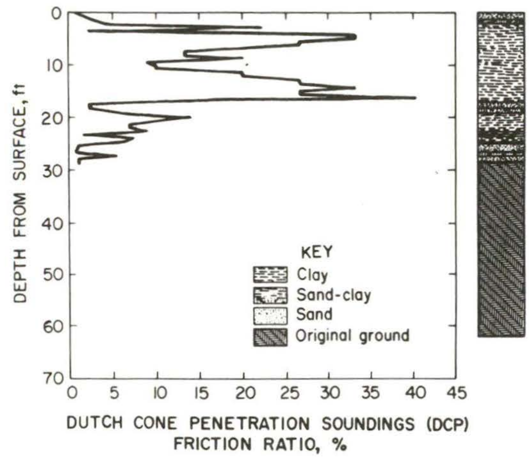


FIGURE A-4.—Electric cone penetrometer soundings, IMC, Noralyn (N-4).

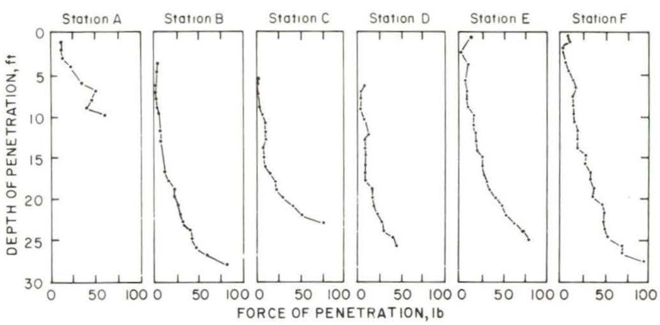


FIGURE A-2.—Hand-driven penetrometer soundings, Mobil, Fort Meade (FM-1).

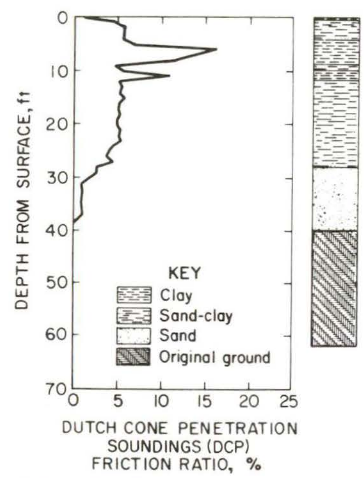


FIGURE A-5.—Electric cone penetrometer soundings, IMC, Greenbay (GB).

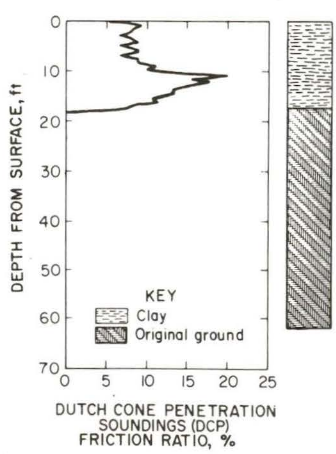


FIGURE A-3.—Electric cone penetrometer soundings, Gardinier, Fort Meade (G-A).

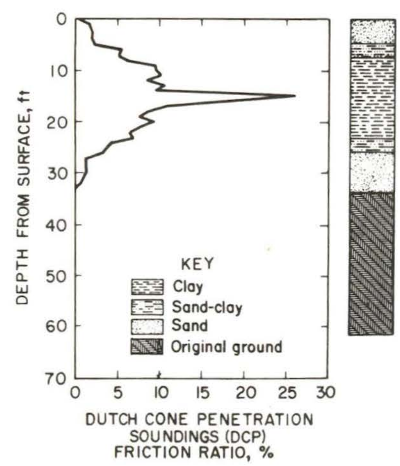


FIGURE A-6.—Electric cone penetrometer soundings, IMC, Clear Springs (CS-2).

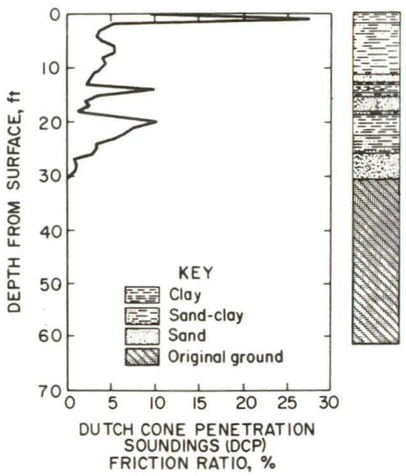


FIGURE A-7.—Electric cone penetrometer soundings, Swift-Mobil, Fort Meade Varn (V).

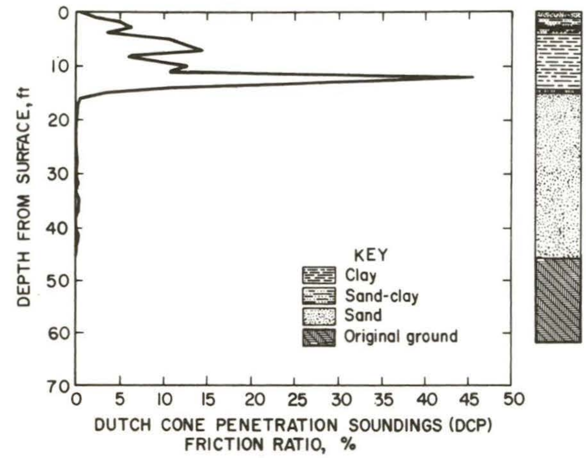


FIGURE A-10.—Electric cone penetrometer soundings, IMC, Noralyn (N-2).

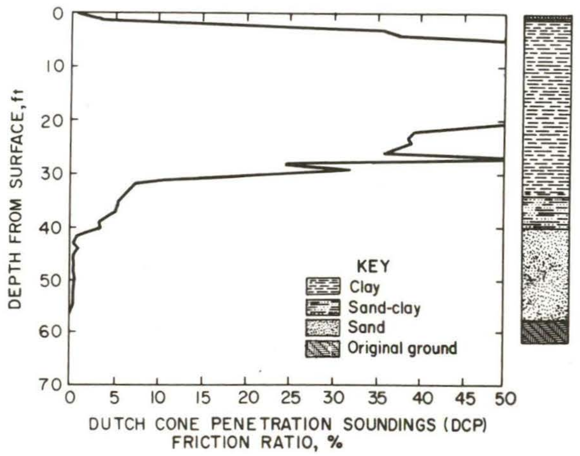


FIGURE A-8.—Electric cone penetrometer soundings, Mobil, Homeland (HO-2).

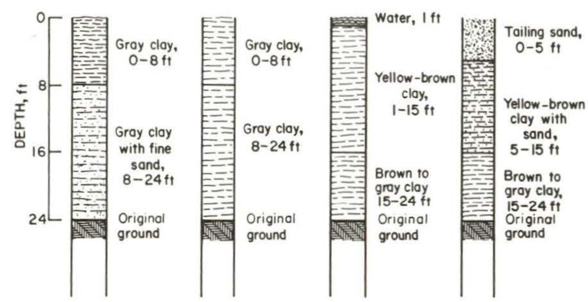


FIGURE A-11.—Core logs from Agrico, Carmachael property pit 9.

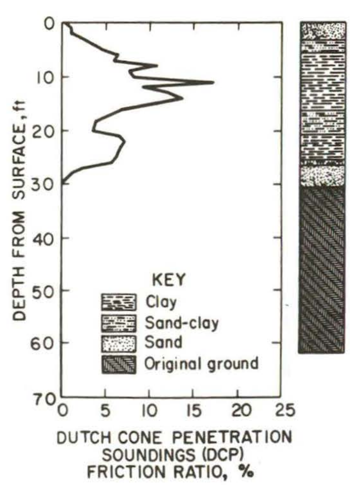


FIGURE A-9.—Electric cone penetrometer soundings, Mobil, Homeland (HO-3).

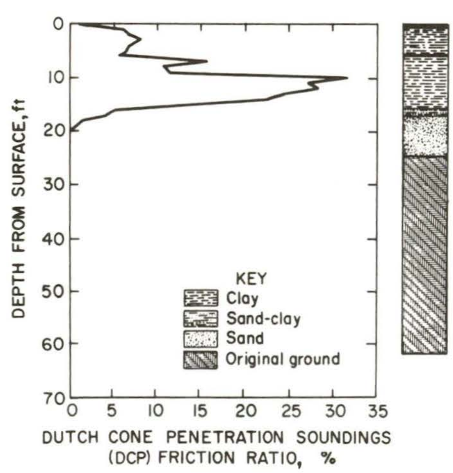


FIGURE A-12.—Electric cone penetrometer soundings, Agrico, Boyette (B-1).

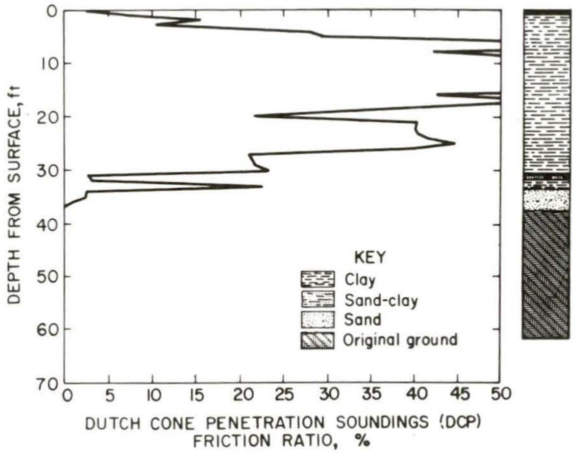


FIGURE A-13.—Electric cone penetrometer soundings, Agrico, Boyette (B-2).

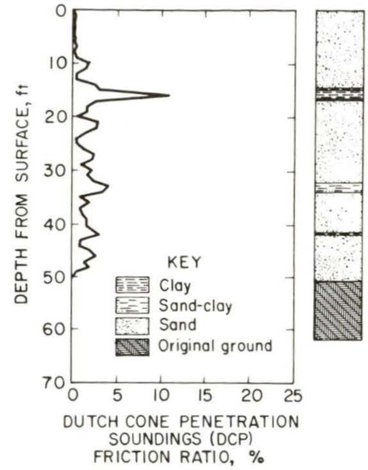


FIGURE A-16.—Electric cone penetrometer soundings, Brewster, Haynsworth (H-2).

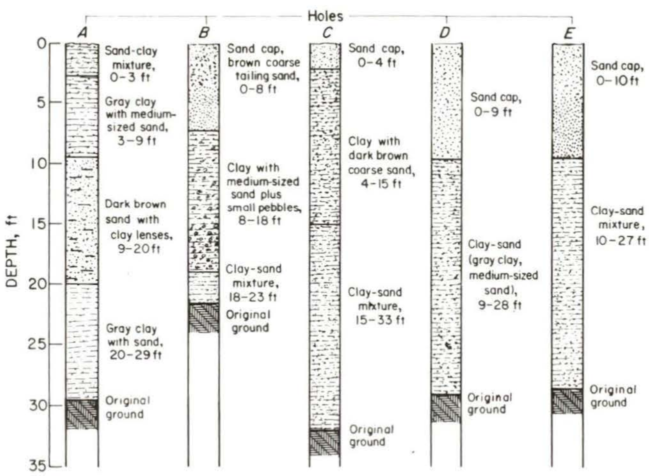


FIGURE A-14.—Core logs from Agrico, Boyette (B-5).

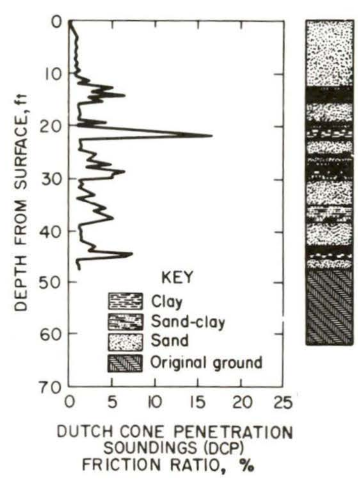


FIGURE A-17.—Electric cone penetrometer soundings, Brewster, Lonesome (L-1).

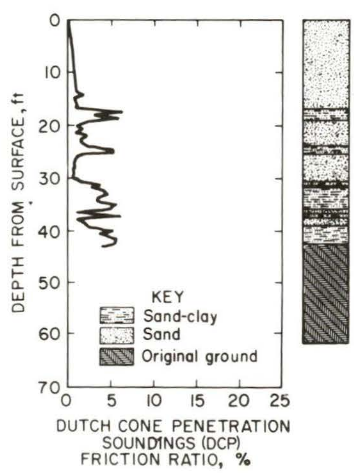


FIGURE A-15.—Electric cone penetrometer soundings, Brewster, Haynsworth (H-1).

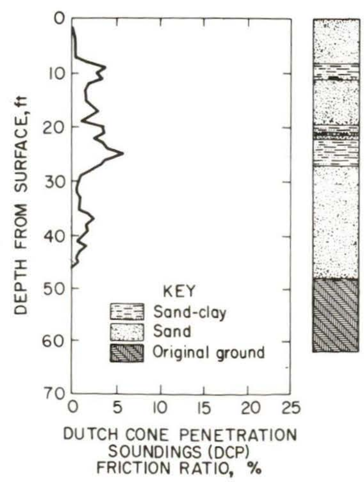


FIGURE A-18.—Electric cone penetrometer soundings, Brewster, Lonesome (L-2).

☆ U.S. GOVERNMENT PRINTING OFFICE : 1984 447-519