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FIELD DEMONSTRATION/EVALUATION OF A RAPID CLAY DEWATERING AND CONSOLIDATION PROCESS USING OTHER WASTES (FIPR/DIPR PROCESS) TO MINIMIZE CLAY SETTLING PONDS

FINAL REPORT

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FINAL REPORT

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March 2009

DISCLAIMER

PERSPECTIVE

Patrick Zhang, Research Director - Beneficiation & Mining

The Florida phosphate matrix (ore) is composed of roughly one-third each of phosphate, clay and sand. The clay must be removed before the upgrading of phosphate using flotation. Therefore, approximately one ton of clay waste (phosphatic clay) is generated for each ton of phosphate rock product. This translates to nearly 100,000 tons/day of waste clay in Florida. In current practice, phosphate clay slurry with an average solids content of about 3% is pumped through pipelines to clay storage ponds where the clay slowly settles. One company practices the sand/clay mix technology in which pre-settled clay is dredged, mixed with sand tailings, and pumped to the reclamation areas. One major problem with the sand/clay mix technique is segregation, which renders a reclaimed land not much better than traditional settling areas.

The clay settling areas occupy up to 40% of mined lands and generally have limited use after reclamation, causing adverse economic and environmental impacts. In the current FIPR Strategic Plan, the highest priority is given to developing technologies to reduce or eliminate clay settling ponds.

In 1991, FIPR initiated an in house research effort to investigate the effect of fibrous materials on dewatering and consolidation of flocculated phosphatic clay. As a result, the FIPR/DIPR process was developed and patented. DIPR stands for Dewatering Instantaneously with Pulp Recycle. The original FIPR/DIPR process involved treating waste clay with a pound of flocculant per ton of clay and 5% waste paper pulp, followed by dewatering on an inclined screen. An evaluation of different scenarios for the use of this process as a reclamation technique indicated an economic disadvantage under 1994 economic conditions.

As the desire to reduce the footprint of clay settling areas intensified, FIPR conducted several workshops on waste clay disposal and utilization during 2002 and early 2003. It became clear that the FIPR/DIPR process still offered the most potential and warranted further development and optimization. Subsequently, the State Legislature provided a special appropriation for evaluating the FIPR/DIPR process in the 2003 Phosphate Bill.

One of the major achievements of the current project is obtaining, by the use of dual polymers, a sand/clay mix that dewaters readily and does not segregate. This breakthrough finding laid a firm foundation for the successful pilot-scale evaluation of the deep cone paste technology, which was also funded by FIPR.

ABSTRACT

Dewatering of various types of fine wastes has been a subject of intense research for many years due to the economic and environmental impacts of their disposal. These wastes include fine phosphatic clays generated by phosphate mining, tailings from the kaolin industry, red mud from processing alumina, and many other and chemical processing wastes. For instance, the phosphate industry in Florida generates an estimated 100,000 tons per day of phosphatic waste clay. This waste containing 3 to 5% solids has historically been pumped to large, above-ground holding ponds, where water is decanted through spillways as the solids slowly consolidate under the impact of gravity to a 15-18% solids level. At this solids content, the ponds slowly dehydrate and form a crust on their surface, which hinders further surface evaporation. Without additional physical efforts to dewater the mass, it may take several decades for the clay to consolidate to a solids content of 25-35%. Because these clay ponds occupy up to 40% of the mined area, they represent a considerable economic penalty to the industry and limit the re-use of tens of thousands of acres of central and north Florida land. This conventional practice also ties up tremendous amounts of water and causes loss of water through evaporation. The economic impact of this conventional disposal practice, coupled with the difficulty of obtaining new mining permits due to this issue, has prompted the mining industry to seek new methods for rapid dewatering of the waste clays.

In this report, the results of laboratory as well as pilot-plant testing of a novel process using hydrocyclones as a rapid dewatering device, as well as sand/clay mixing, are discussed. Results indicate that up to 80% of the water could be recovered and recycled back to the plant in a few minutes. A soil of more than 45% solids content and 1:1 sand/clay ratio could be produced and used to fill mine cuts for land reclamation. The technical, economical, and practical aspects of this process are presented.

ACKNOWLEDGMENTS

All the researchers in this project would like to express their sense of appreciation to the Florida Institute of Phosphate Research for their financial support of this project. Special thanks to Mosaic personnel for their in-kind support. We also appreciate the helpful discussions with Dr. Patrick Zhang, Mr. Mike Lloyd, and Dr. Paul Clifford.

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EXECUTIVE SUMMARY

An in-house research effort was initiated at the Florida Institute of Phosphate Research (FIPR) in 1991 to investigate the effect of fibrous material on the flocculation and dewatering of phosphatic clays. Several dewatering (solid/liquid) techniques were investigated, including sedimentation thickening, filtration, centrifugation, dewatering on screens, and seepage-induced dewatering and consolidation. As a result, the FIPR/DIPR process was developed and patented. DIPR stands for Dewatering Instantaneously with Pulp Recycle. In the original FIPR/DIPR process, phosphatic clay was treated with a flocculant (at about one pound per ton of clay solids) and 5% waste paper pulp followed by dewatering on an inclined screen.

In a subsequent FIPR-funded project, Dr. Hassan El-Shall and BCI evaluated different scenarios for the use of the process as a reclamation technique. The study included an evaluation of the consolidation behavior, disposal alternatives, and costs of implementing the process.

Consolidation testing was completed on untreated clay and clay treated with polymer and pulp using the restricted flow consolidation (RFC) test in the BCI laboratory. Results of laboratory testing allowed BCI to develop consolidation parameters and to predict the behavior of clay and FIPR/DIPR mix. Based on the consolidation parameters developed for the clay and FIPR/DIPR mix, BCI analyzed dilute clay disposal in conventional clay settling areas and FIPR/DIPR mix in low embankment areas built around mined-out cuts. The conclusion was that FIPR/DIPR was more expensive than the conventional process due to the costs for flocculant and fiber. However, no attempt was made to analyze utilization of FIPR/DIPR based disposal techniques in mined-out areas without impounding.

In light of the renewed interest in finding a solution to the phosphatic clay disposal problem from the perspective of both local governments and the phosphate industry, FIPR sponsored several workshops on issues related to clay disposal and utilization during 2002 and 2003. It became apparent from those workshops that further research was warranted to evaluate and further develop the FIPR/DIPR process on a larger scale, including evaluation of several sources of fiber as well as various scenarios of clay and/or sand-clay disposal possible with this process.

OVERALL GOALS:

A. Demonstrate the technical, practical, and economic feasibility of the FIPR/DIPR process to reduce clay settling areas

B. Demonstrate that the clay disposal areas reclaimed by this process are of more economical value and better use than the ones reclaimed by current techniques

SPECIFIC OBJECTIVES:

- Evaluate the performance, cost-effectiveness, and practical aspects of using different sources of fibers (in addition to paper waste) such as sewage sludge, yard debris, etc., as additives in the FIPR/DIPR process
- Evaluate the technical and economic feasibility of different clay disposal techniques including the use of hydrocyclones and/or other techniques for:
  - flocculation and thickening devices for clay using the FIPR/DIPR mixture
    - mixing dewatered tailings and flocculated FIPR/DIPR clay for disposal as high solids content sand/clay mixture
    - dewatering a mixture of sand, clay, and fiber to obtain a high solids content product for disposal

This report describes all performed activities and collected data during two phases of the project including laboratory investigations, bench-scale cyclone experiments, and field testing of the pilot plant. The project activities are collaborative efforts between the University of Florida and Met Pro Supply, BCI, and Penn Pro, Inc.

PHASE I ACTIVITIES

Survey for Fiber Sources and Logistics

We visited solid waste managers at Polk, Hardee, and Hillsborough Counties and found that over 100,000 tons/year each of waste mixed paper, cardboard, and yard waste could be available at Polk County with only shipping and handling costs. The pulping costs were also found to be reasonable. However, after running the pilot plant, it became obvious that fiber addition might not be beneficial to consolidation of the produced sand/clay mixture.

Lab Testing

More than 10 anionic (>30% charge) polymers of high molecular weight (10-26 M) and their combinations with cationic (>50% charge) polymers (MW 1-5 M) were tested. Most of these polymers resulted in recovering 80% of the water by dewatering on a 35 mesh screen for one minute, giving a product containing >18% solids. The best reagent schemes include adding a coagulant (cationic polymer) followed by a high molecular weight anionic polymer (flocculant) to produce a sand/clay mix that does not segregate and dewaters quickly on a dewatering screen.

Hydrocyclone Semi Pilot Testing

Met Pro modified a 6-inch hydrocyclone and associated sump, pumps, and cyclone products receiving tanks. The test equipment was used to test different polymers and their combinations, point of additions, dosage, and polymer concentration, dilution of clays, flow rates, pressure drop, etc. A 100 gpm flow rate at 6-10 psi pressure drop combined with adding polymer/coagulant combination at three or more different points was found to produce flocculated clays that could be dewatered in the cyclone. The results were encouraging. Adding sand to the cyclone sump produced a homogeneous sand/clay mix in the cyclone underflow. The results were very encouraging since the product was a flocculated mixture that did not segregate. It also contained high solids content (>30%) and consolidated faster under its own weight. Based on the obtained results, a 200 gpm test unit was constructed at the Mosaic Co. South Fort Meade Plant.

Pilot Plant Testing

During the months of May, June and July, 2005, the pilot plant was operated as designed for several hours at a time. Clear water and high solids content slurry were produced. The dewatered sand/clay mixture (cyclone underflow) was collected in the small clarifying cone. Because of its high solids content, the mixture needed to be manually moved from the cone underflow. The mixture was further dewatered on the static screen. Due to some design problems, the clarifier did not work properly at times, resulting in solids in the overflow.

Using reagents from three different suppliers, several statistical designs were conducted to generate technical data about the process performance. Two designs were used involving 2^2 (including two variables at two levels each) and 2^3 (involving three variables at two levels each). In the first design, the variables included the dosages of the flocculant and coagulant. In the second design, the sand/clay ratio (SCR) was used as the third variable. The percentage of total solids content and the SCR were the response variables in the first design. A third statistical design was used to test reagents from the third supplier. After changing the parameters for each run, the plant was operated for 30 minutes at steady state before collecting samples for lab analysis.

The obtained data suggested that depending on the sand/clay ratio, products of total solids content higher than 55% could be obtained. Most importantly, no sand segregation was noticed except at very high (4.0) SCR.

In addition to the above statistical designs, two test pits (4 × 4 × 4 feet) were filled with product. One was half full of water before pumping the product under water to test the disintegration of the flocs and to simulate filling a mine cut containing water. The second pit was dry and the product was tested by coring it at different times to analyze for consolidation and segregation of the sand. The results indicated that the product did not segregate even if deposited under water. Interestingly, the produced mixture dewatered in the pits to a level that could have a light load bearing capacity (after 72 hours of consolidation).

A preliminary cost analysis conducted by Penn Pro suggested that the FIPR/DIPR process cost might range between \$0.95 and \$1.60 per ton of phosphatic clay.

On the basis of the lessons learned during the pilot plant operation and the preliminary cost analysis, modifications to the pilot plant were proposed and a second phase was funded by FIPR. Details of the activities conducted in the second phase are given in Part II of this report.

PHASE II ACTIVITIES

Met Pro Supply added necessary modifications to the pilot plant including a clay feed tank, a sand belt feeder, rakes to the clarifier, a paper shredder, a new cyclone sump and pump., as well as necessary valves. Penn Pro supplied necessary controls. The objective of running the modified pilot plant was to produce dewatered mixtures to be tested for consolidation rate, permeability, and load-bearing capacity, as well as to generate necessary operating and design data that could be used in the economic analysis.

Geotechnical Testing

BCI's primary assignments in the project involved sampling and testing of the clay mix products produced by the plant to determine settling and consolidation properties, and to evaluate the mixtures for ultimate load bearing capability.

The Phase 2 tasks completed by BCI included participating in the planning of modifications to the pilot plant and in field activities to implement the changes. Three pipe columns consisting of 25-foot lengths of HDPE pipe were erected adjacent to the plant, and were filled with clay mix products from the plant. The columns provided a height of fill representative of a field disposal situation, allowing monitoring of the settling and self-weight consolidation that occurs in plant-scale operations. The columns were fitted with valve ports for sampling and monitoring pore water pressures at various times.

During operation of the pilot plant, the pipe columns were filled with three different products: clay/fiber mix, clay/sand mix, and clay/sand/fiber mix. Grab samples of each mix were taken as the pipes were being filled. Samples of the raw untreated clay being fed to the plant were also taken. The samples were taken to the BCI laboratory for geotechnical testing and analysis, as described herein.

Following the filling of each pipe column, periodic measurements were taken to determine the height of the consolidating clay mix. Pore pressure measurements were also taken to determine the percentage consolidation of the mix. As consolidation approached completion, samples were taken from sample ports on the columns.

The samples returned to the laboratory were tested for moisture (solids) content, and percent sand-size material (using a No. 140 sieve, as is customary in the industry).

Selected samples were tested for plasticity (Atterberg Limits), organic (fiber) content, and settling tests. Composited samples from each column were mixed and tested in a constant rate of strain consolidation (CRSC) test apparatus. After consolidation, the shear strength of the samples was measured using direct simple shear (DSS) equipment. The shear strength results were used to calculate ultimate and allowable bearing capacities for the three mixtures.

The laboratory and field test results and data were analyzed and evaluated to compare consolidation and strength behavior among the three clay mix products. Consolidation parameters were determined based on the column tests and CRSC tests, using the computer program SLURRY, which was developed for FIPR under a research grant to Ardaman & Associates in 1986. The consolidation parameters can be used to predict consolidation rates and final solids contents for various mining and reclamation scenarios. In this manner, mining companies can make economic analyses to compare the costs of implementing the FIPR/DIPR process with their current costs of clay disposal and land reclamation.

Based on the data collected and the testing and analyses reported herein, the following general conclusions can be made:

The plasticity index values (Atterberg Limits) for the composite clay samples for the column fills had PI values of 64, 125, and 82 for clay/ pulp mix in Column 1, clay/ sand mix in Column 2, and clay/sand/pulp mix in Column 3, respectively. Although this range is large, it indicates that the plasticity was generally in the lower range encountered for phosphatic clay.

The total solids content after consolidation was significantly higher in Column 2 (clay/sand mix) than in Column 1 (clay/pulp mix). Column 2 also had the highest plasticity clay, which would imply the worst consolidation characteristics.

The highest clay solids were obtained in Column 3 (clay/sand/fiber). However, this column had leakage out of the bottom of the column, while produced induced seepage forces, which likely contributed to the higher solids content.

The consolidation results, although to a large extent masked by operational variations between the three tests, do not indicate that addition of fiber to clay, as compared to adding sand to clay, is effective in improving settling and consolidation behavior.

The major improvements to settling and consolidation of the clays in this test program can be attributed to (1) effective flocculation of the clay, which accelerated both the settling and consolidation in the pipe columns, and (2) the admixing of tailings sand, which significantly increased the unit weight and hence the self-weight stresses causing consolidation of the clay/sand mix.

It may be concluded that for the same consolidation conditions and the same applied loading conditions, the bearing capacity of a 2:1 sand/clay mix is substantially higher than a clay/fiber mix. However, the allowable bearing capacity of any phosphatic clay mixture that is consolidated under self-weight alone, even after some drying and desiccation, is too low for practical construction purposes. In order to achieve practical values of allowable bearing capacity, either surcharging, desiccation, or chemical stabilization must be accomplished.

Economic Analysis

Penn Pro, Inc. conducted an economic analysis of FIPR/DIPR (UF Process) for thickening phosphatic clay with the Deep Cone Thickener included. The analysis is used to calculate the cost of this new process as compared to the flocculation disposal technique currently used by the industry. The study considered a 5MM TPY mine basis with 28% clay and 28% product in the ore. Under the current practice using disposal of flocculated clays, about ten clay ponds are required for a 25 year mine life versus only two for the revised UF process. In this estimate, most of the plant sand is used and the predicted production of 45% solids content for the sand clay mixture. This means only the plant GMT tails pump will be needed with a short length of pipe instead of much longer pumping lines.

With a 25% contingency, the final estimated life-of-mine cost is $40,038,099 for this revised process. Using the Net Present Value method, a net savings $1.42 per ton of phosphate was calculated as compared to the current practice. It is also possible that cost reductions may occur from further process development, particularly in the Deep Cone thickening system itself.

The conclusion is that further process development is needed, including a full-size 24” or larger cyclone test. A cost estimate should be conducted using a 1:1 SCR and the proposed process flow diagram. In addition, the number of deep cone thickeners should be recalculated based on lab testing of the cyclone underflow, which was not done in the present estimates.

DETAILED PROJECT ACTIVITIES

INTRODUCTION

Magnitude of the Waste Clay Disposal Problem

The Florida phosphate matrix (ore) is composed of roughly one-third each of phosphate, clay and sand. The clay must be removed before upgrading of the phosphate product using flotation. Therefore, approximately one ton of clay waste (phosphatic clay) is generated for each ton of phosphate rock product. This translates to nearly 100,000 tons/day of waste clay in Florida. Under current practice, the phosphate clay slurry with an average solids content of about 3% is pumped through pipelines to clay storage ponds where the clay slowly settles (see figure 1).

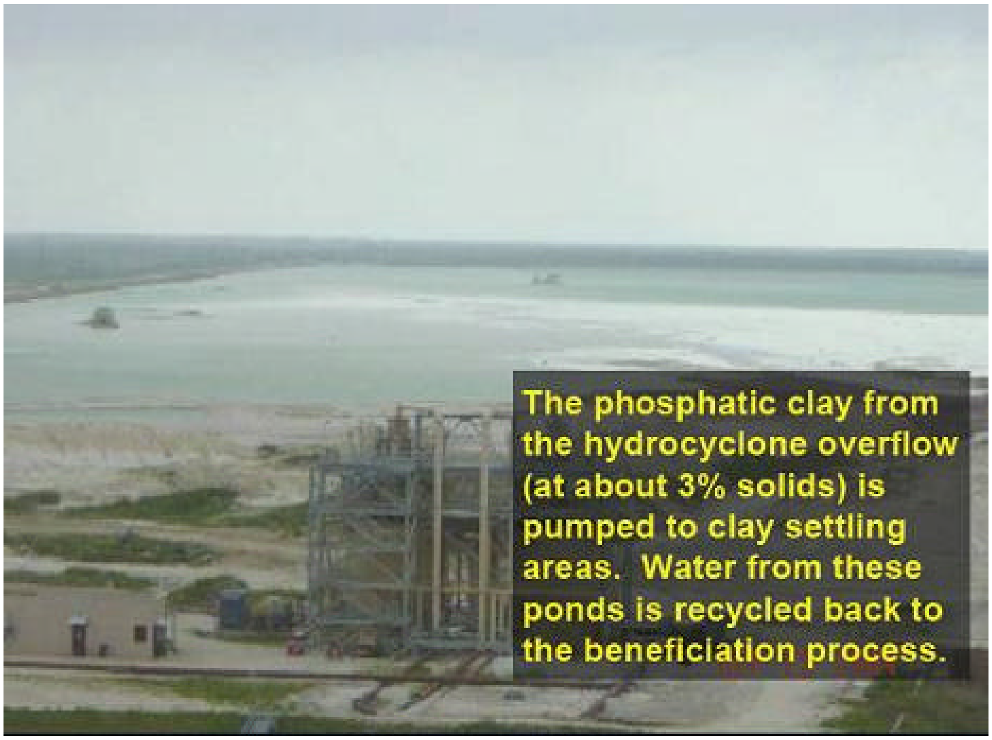


Figure 1. A Phosphatic Clay Settling Area.

Although impounding may be the most economical method of waste clay disposal, it has several major disadvantages. Clay settling ponds occupy about 40% of mined lands and generally have limited use after reclamation, causing adverse economic impacts. The waste clay not only ties up a large amount of water, but significant amounts of water are also lost through evaporation from the clay settling areas, which can occupy up to 800 acres each.

In the recently updated FIPR Strategic Plan, the highest priority is given to developing technologies to reduce or eliminate clay settling ponds.

Evolution of the FIPR/DIPR Project

An in-house research effort was initiated at FIPR in 1991 to investigate the influence of fibrous material on the flocculation and dewatering of phosphatic clays. Several dewatering (solid/liquid) techniques were investigated, including sedimentation thickening, filtration, centrifugation, dewatering on screens, and seepage-induced dewatering and consolidation. As a result, the FIPR/DIPR process was developed and patented. DIPR stands for Dewatering Instantaneously with Pulp Recycle. In the original FIPR/DIPR process, phosphatic clay is treated with a flocculant (at about a pound per ton of clay solids) and 5% waste paper pulp followed by dewatering on an inclined screen.

In a subsequent FIPR-funded project, Dr. Hassan El-Shall and BCI evaluated different scenarios for the use of the process as a reclamation technique. The study included an evaluation of the consolidation behavior, disposal alternatives and costs of implementing the process.

Consolidation testing was completed on untreated clay and clay treated with polymer and pulp using the restricted flow consolidation (RFC) test in the BCI laboratory. The results of the laboratory testing allowed BCI to develop consolidation parameters and to predict the behavior of the clay and the FIPR/DIPR mix. Based on the consolidation parameters developed for the clay and the FIPR/DIPR mix, BCI analyzed dilute clay disposal in conventional clay settling areas and the FIPR/DIPR mix in low embankment areas built around mined-out cuts. The conclusion was that the FIPR/DIPR mix was more expensive than the conventional process due to the costs for flocculant and fiber. However, no attempt was made to analyze utilization of FIPR/DIPR-based disposal techniques without impounding.

In light of the renewed interest in finding a solution to the phosphatic clay disposal problem from the perspective of both local governments and the phosphate industry, FIPR sponsored several workshops on issues related to clay disposal and utilization during 2002 and 2003. It became apparent from those workshops that further research was warranted to evaluate and further develop the FIPR/DIPR process on a larger scale, including evaluation of several sources of fiber as well as various scenarios of clay and/or sand-clay disposal possible with this process.

A SURVEY OF FIBER SOURCES AND LOGISTICS

After visiting solid waste managers at Polk, Hardee, and Hillsborough Counties, we can summarize the available resources such as mixed waste paper and cardboard waste.

Mixed Waste Paper

There are 100,000 tons/ year of mixed waste paper that could be delivered free of charge if the cost of delivery is less than $20 per ton at Polk county's landfill. This could be enough for the 3 million tons/year of clay treatment plant at a usage rate of 3% fiber to clay ratio. The Hardee County landfill does not collect waste paper. Hillsborough County, however, sells all of the collected paper at $65 per ton, which could be a major cost.

Cardboard Waste

There are also 200,000 tons/year of cardboard waste at the Polk County and Hillsborough facilities, which is enough for two (3 million tons/year of clay production) plants at a usage rate of 3% fiber to clay.

Cost of Pulping

Pulping can be done in a waste disposer machine Series A (15" Rotor/Turntable) of 5-7.5 H.P. manufactured by Master Disposers, Inc. of Cincinnati, Ohio. The machine handles 2.6 tons/hour. For a total of 12 tons/ hour of the needed fiber at a usage rate of 3%, a total of 5-8 machines could be used. At a price of $10-15K per machine, the capital cost would be only $75-120K. This is a small cost compared with other capital equipment. However, considering other needed handling equipment, the cost of pulping may be reasonably assumed to reach $250K. Once again, depreciating this cost over 5 years, the capital cost of pulping may be estimated as $0.02 per ton of clays. Using a factor of 250% to represent other costs, then the estimated cost of pulping is $0.07 per ton of clays.

Yard Waste

The Polk County landfill has enough to operate several plants at shipping cost of $3-10 per ton depending on the distance. Grinding this waste can be done using a CBI grizzly mill from Continental Biomass Industries, Inc., Newton, NH. The specifications are listed below. The capacity, however, is double what is needed for our application (3% usage rate of 3 million ton clay production plant) (http://www.cbi-inc.com).

Mill Size	Total Weight	RPM	Horsepower Electrical/Diesel	Capacity TPH
36 x 36 in	16,600	750	200-300	25

The web site (http://www.banditchippers.com) indicates a cost of about $10 per ton total cost. Thus, the cost of grinding yard waste will be about $0.10-0.30 per ton of clay depending on the usage rate (1-3%).

Wastewater Sludge

There are different types of sludge that are produced by wastewater treatment facilities. Getting sludge to the plant from Lakeland would work the same way it does to get it to ranchers—via 7,000 gal. tank trucks. Lakeland has two plants. The larger plant has two products: a Class B that is land-applied (ranchers), which is produced at 1.1 million gal./day containing 1.1% solids. They have another product called a secondary bioset, an AA product, which is heat-treated and mixed with lime and used as a soil amendment. Lakeland produces about 650 tons/month of this 1:1 sludge/lime mixture at ~27% solids. The second plant produces an AA liquid at 3% solids (much like the UF plant used in the lab tests reported above) that has a 15K gal./day output.

The cost as well as the logistics can be discussed with the plant personnel as it is related to volumes, etc. However, based on the lab data, we do not think there is any advantage to using the sludge, as it will require more storage capacity with no added advantage over other fibers.

LAB TESTING

More than 10 anionic (>30% charge) polymers of high molecular weight (10-26 M) and their combinations with cationic (>50% charge) polymers (MW 1-5 M) were tested. These flocculants and coagulants were obtained from three different suppliers (Ciba Specialty Chemicals, Virginia, USA; SNF, Georgia, USA; and Hengju, Beijing, China). Evaluation criteria included percent solids in dewatered product, strength of the flocs, and polymer dosage. Most of these anionic polymers resulted in recovering 80% of the water by dewatering on a 35 mesh screen for one minute, giving a product containing >18% solids (see Table 1). The best reagent schemes include adding a coagulant (cationic polymer) followed by a high molecular weight anionic polymer (flocculant) to produce a sand/clay mix that does not segregate and dewaters quickly on a dewatering screen. Mixing 2:1 sand:clay on the dewatering screen produced a 45% solids content mixture.

Various waste additives were tested, including newspaper pulp, cardboard pulp, activated sewage sludge, and yard waste. All these wastes were added as shredded material (except the sludge) during pulping with phosphatic clays and before dewatering on the screens. The sludge of 3% solids content was added as a suspension to the phosphatic clay slurry. The results are listed in Table 2.

HYDROCYCLONE SEMIPILOT TESTING

Met Pro modified a 6-inch hydrocyclone and associated sump, pumps, and cyclone products receiving tanks. The equipment was used to test different polymers and their combinations, point of additions, dosage, and polymer concentration, dilution of clays, flow rates, pressure drop, etc. A 100 gpm flow rate at 6-10 psi pressure drop combined with adding polymer/coagulant combination at three or more different points was found to produce flocculated clays that could be dewatered in the cyclone. Due to high flow rate as compared to the total sample volume collected from Cargill (600 gallons each trip), it was difficult to run for a longer time than 5 minutes and only open circuit was used. However, the results were encouraging. Testing the addition of flocculated clays on a sand layer on a screen as a possible route has not been successful at this point. This led us to add the sand to the cyclone sump and produce sand/clay mix from the cyclone underflow. The results were extremely encouraging since the product was a flocculated mixture that did not segregate. It also contained high solids content (>30%) and consolidated faster on its own weight. Based on the obtained results, a 200 gpm test unit was constructed at the Mosaic Co. South Fort Meade Plant. A conceptual flow diagram of the pilot plant is shown in Figure 2 and a picture is given in Figure 3.

Table 1. Effect of Various Polymers on Dewatering Phosphatic Clays Mixed with 3% by Weight Waste Newsprint.

Flocculant	Product % Solids	Flocculant	Product % Solids
Percol 156	18.6	Magnafloc 351	16.4
Hengfloc 64014	16.6	Magnafloc 919	17.0
Magnafloc 1011	16.0	Magnafloc 24	17.6
Magnafloc 336	19.5	Magnafloc 336/ Hengfloc 64014 Mix	17.1
Magnafloc 336/ Magnafloc 919 Mix	14.0	Percol 156/ Hengfloc 64014 Mix	16.7
Magnafloc 336/ Percol 156 Mix	14.8	Magnafloc 919/ Hengfloc 64014 Mix	16.9
Magnafloc 336/ Magnafloc 351 Mix	17.3	Magnafloc 919/ Hengfloc 64014 Mix	16.5

Table 2. Effect of Fiber Type on Product Solids Content.

Fiber Type	Fiber % Used	Product Solids %
Sewage Sludge	10%	15.2
	25%	14.5
	50%	14.4
Cardboard	1%	15.3
	3%	16.2
	5%	17.4
Yard Waste	1%	15.4
	3%	16.4
	5%	18.1
Newspapers	1%	14.8
	3%	15.6
	5%	16.3

Notes: Feed solids % = 3.1 %, 0.25 lb/t coagulant (Magnafloc 371), 1.0 lb/t flocculant (Hengfloc 64014)
In the case of sewage sludge, the percent is based on total weight of (clay + water). For other tests, the fiber % is a percent of fiber to the dry weight of clay.

The data indicate that yard waste can produce a dewatering effect as good as other wastes, if not slightly better.

PHASE I: PILOT PLANT TESTING

During the months of May, June and July, 2005, we ran the pilot plant at Mosaic's South Fort Meade plant. Several statistical designs to generate technical data about the process performance were conducted.

Running the Plant

The pilot plant consisted of the following items:

- A cyclone sump (mixing tank where sand is added to be mixed with the incoming clay together with the settled solids from the cyclone overflow clarifier)
- A sand screw feeder
- A coagulant dilution and feeding unit to feed a dilute (0.1%) coagulant solution (cationic polymer) to the cyclone feeding sump
- A static mixer in the line after the cyclone feeding pump
- A flocculant mixing station feeding the anionic flocculant solution (0.05% solution of a high molecular weight anionic polyacrylamide)
- An eight inch diameter hydrocyclone running at 6-8 psi
- Feeding points on the cone of the cyclone for more flocculant addition
- A 4 ft. diameter clarifier with a 45 degree cone angle and rakes to receive the cyclone overflow. Clear water from this clarifier is recycled for use in the beneficiation plant and the settled solids (underflow from the clarifier) flows to the cyclone feeding sump.
- A 2 ft. diameter deep cone (45 degrees cone angle) settling tank to receive the underflow from the cyclone for further dewatering and consolidation of the sand/clay mixture. Clear water returns back to the clarifier.
- A vibrating feeder to feed sawdust fiber to the sand/clay mix product from the small dewatering cone
- A dewatering sieve bend returning the underflow to the clarifier, and the overflow sand/clay mix is transferred to the final product receiving tank before pumping to the test pit, testing columns, or the disposal area

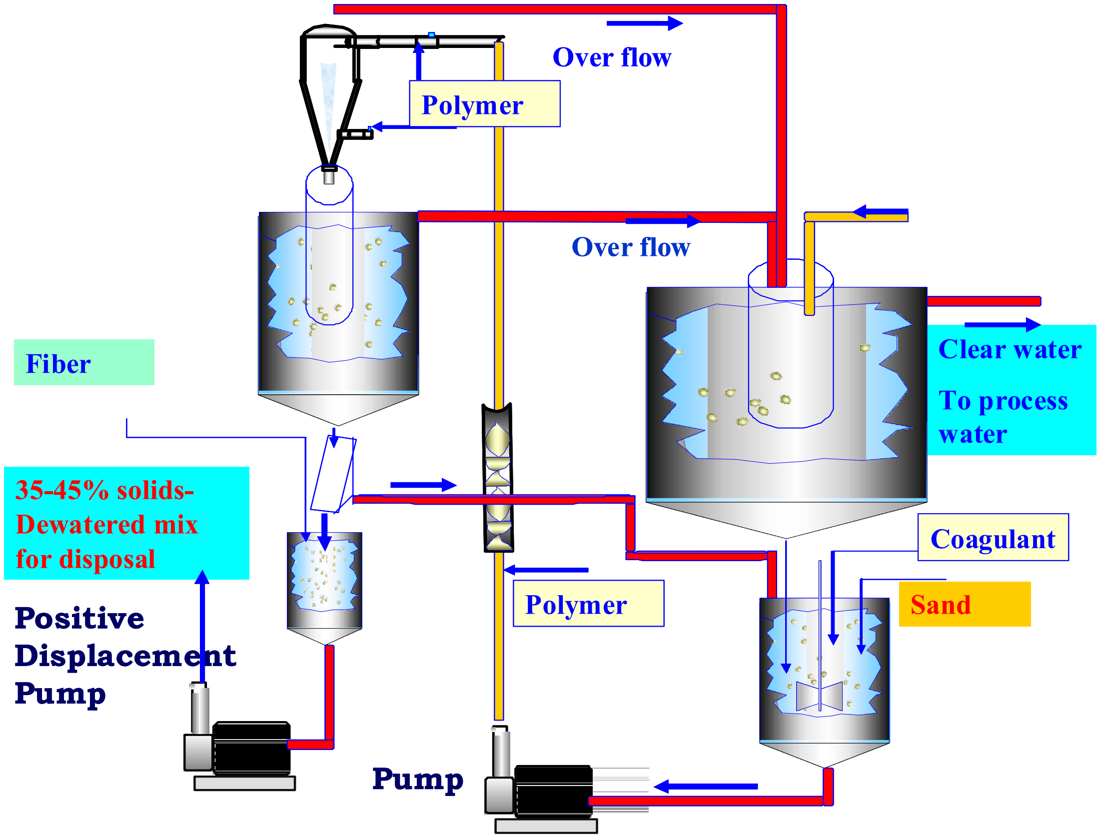


Figure 2. Conceptual Flow Diagram of the Pilot Plant for FIPR/DIPR Process.

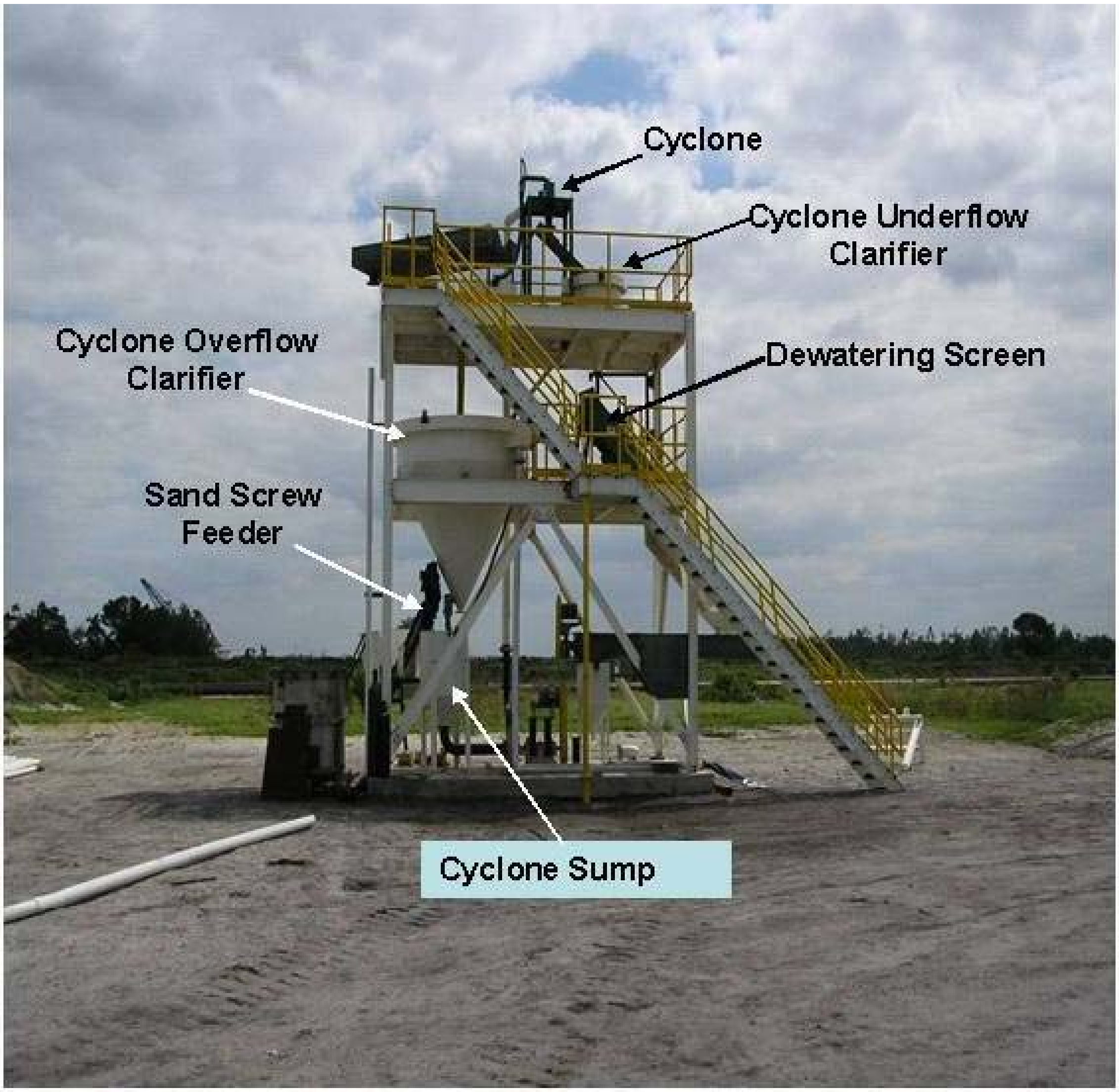


Figure 3. Pilot Plant at South Fort Meade Phosphate Beneficiation Plant.

The plant was run as designed for several hours at a time. Clear water and high solids content slurry were produced, as shown in Figures 4 and 5. The dewatered sand/clay mixture (cyclone underflow) was collected in the small clarifying cone. Because of its high solids content, the mixture needed to be moved to the cone underflow. The mixture was further dewatered on the static screen, as shown in Figure 5.

Clear Water Coming Off the Clarifier During a Smooth Run

Figure 4. Clear Water from the Clarifier Overflow.

Due to some design problems (as explained under "Lessons Learned"), the clarifier did not work properly at times, producing solids with the overflow as shown in Figure 6.

Cyclone Underflow to the Clarifying Cone

Dewatered Sand/Clay Mix on the Static Screen

Figure 5. Cyclone Underflow Flowing to the Dewatering Cone and the Static Screen.

Figure 6. The Clarifier Under Improper Running Conditions.

Statistical Design Runs

Two designs were used involving 2^2 (including two variables at two levels each) and 2^3 (involving three variables at two levels each). Both designs have a central point at the mid-level of the variables (Tables 3 and 4, respectively). In the first design, the variables include the dosages of the flocculant and coagulant obtained from the first supplier. In the second design, the sand/clay ratio (SCR) is used as the third variable. The percentage of total solids content and the SCR are the response variables in the first design. It should also be mentioned that in all of these tests there was no clarification allowed in the cyclone underflow dewatering cone; also, that after changing the parameters for each run as given in Table 3, the plant was operated for 30 minutes at steady state before collecting samples for lab analysis.

Table 3. Effect of Flocculant and Coagulant Dosages on % Solids and Sand/Clay Ratio.

Sample ID	Conditions		% Solids	SCR
	F	C		
1	-	-	56.1	4.0
2	+	-	34.2	2.0
3	-	+	26.0	1.9
4	+	+	52.2	4.0
5	0	0	42.4	2.96

The (+) and (-) represent the high value, while 0 is the mid-point.
F: Flocculant-anionic polymer [0.5-2.5 lb/t]; C: Coagulant-Cationic polymer [0.1-1.1 lb/t]; SCR: Sand clay ratio; Clay in the feed is 2.2 %.

The data in Table 3 suggest that products of total solids contents as high as 56% could be obtained. Statistical analysis of the data gives the contour plots for the % solids content as a function of reagent dosage, as shown in Figure 7. The data also indicate that SCR should be controlled as a variable, not as a response. This was considered in the second design. The data given in Table 4 were obtained by testing reagents from the second supplier.

It is clear that using an SCR of 1-1.5 produces a mixture of higher solids content that can dewater further in the cone, on the screen, and in the disposal area, as indicated by the clear water we observed on the surface of the settled mixture. This increase in solids content after decanting surface water can be clearly seen in Table 4 and in Figure 8. Most importantly, more than 45% solids content (1-1.5 SCR) is obtained after 48 hours of settling. It should be emphasized that no sand segregation was noticed except at very high (4.0) SCR. In both designs the mid-point SCR proved to be an excellent condition for operation of the pilot plant to produce a high solids content product with no segregation of sand from clay.

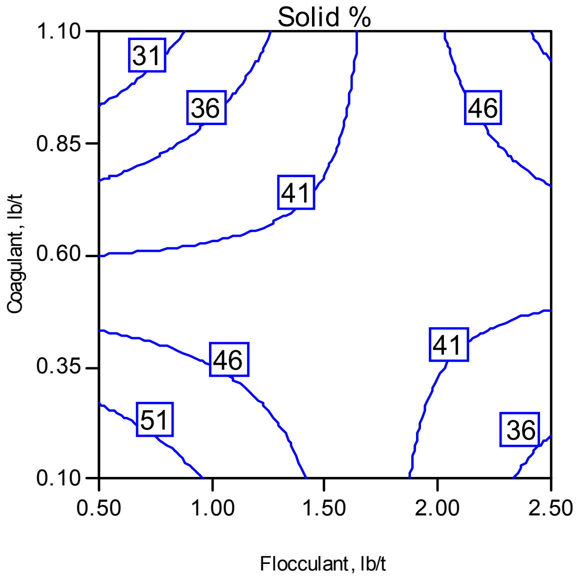


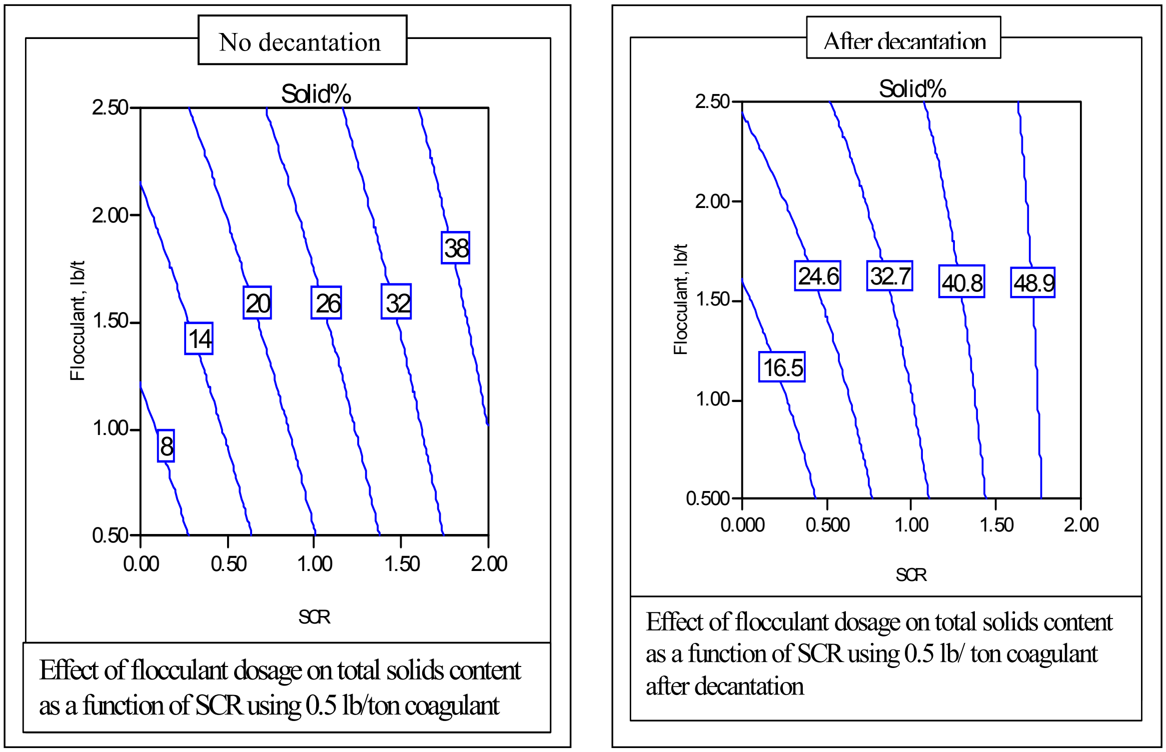
Figure 7. Total Solids Content as a Function of Reagent Dosage (at 1.5 SCR).

A third statistical design was used to test reagents from the third supplier. The design matrix and the data obtained are given in Table 5. Statistical analysis of the data gives the contour plots for the % solids content as a function of reagent dosage, as shown in Figure 9. In this design also, the data suggest that using 1-1.5 SCR can produce a mixture of up to 39 % solids without decantation.

Table 4. Effect of Flocculant and Coagulant Dosages on % Solids in the Cyclone Underflow as Obtained in the Second Design.

Sample ID	Conditions			% Solids	
	F	C	SCR	Without Decantation of Surface Water	After Decantation of Surface Water after 48 Hours of Settling
1	-	-	-	3.2	6.0
2	-	-	+	36.4	52.6
3	-	+	-	7.1	10.7
4	-	+	+	39.3	61.5
5	+	-	-	16.1	24.6
6	+	-	+	43.4	53.1
7	+	+	-	14.8	20.4
8	+	+	+	41.9	50.2
9	0	0	0	36.2	52.3
10	0	0	0	38.0	53.5
11	0	0	0	37.2	54.2

The (+) and (-) represent the high value, while 0 is the mid-point. F: Flocculant-anionic polymer [0.5-2.5 lb/t]; C: Coagulant [0.0-2.0 lb/t]; SCR (design) : Sand/clay ratio [0-2]; and Clay in the feed is 3.2 %.



Effect of flocculant dosage on total solids content as a function of SCR using 0.5 lb/ton coagulant

Effect of flocculant dosage on total solids content as a function of SCR using 0.5 lb/ ton coagulant after decantation

Figure 8. Effect of Flocculant Dosage on Total Solids Content Using 0.5 Lb./Ton Coagulant at Various SCRs.

Table 5. Effect of Flocculant and Coagulant Dosages and SCR on % Solids in the Product According to the Third Statistical Design.

Sample ID	Conditions			% Solids
	F	C	SCR	
1	-	-	-	10.96
2	-	-	+	52.6
3	-	+	-	9.86
4	-	+	+	40.12
5	+	-	-	16.0
6	+	-	+	55.02
7	+	+	-	12.6
8	+	+	+	40.6
9	0	0	0	29.2
10	0	0	0	30.5
11	0	0	0	28.8

The (+) and (-) represent the high value; while 0 is the mid-point. F: Flocculant-anionic polymer [0.5-2.5 lb/t]; C: Coagulant [0.0-2.0 lb/t]; SCR : Sand clay ratio [0-2].

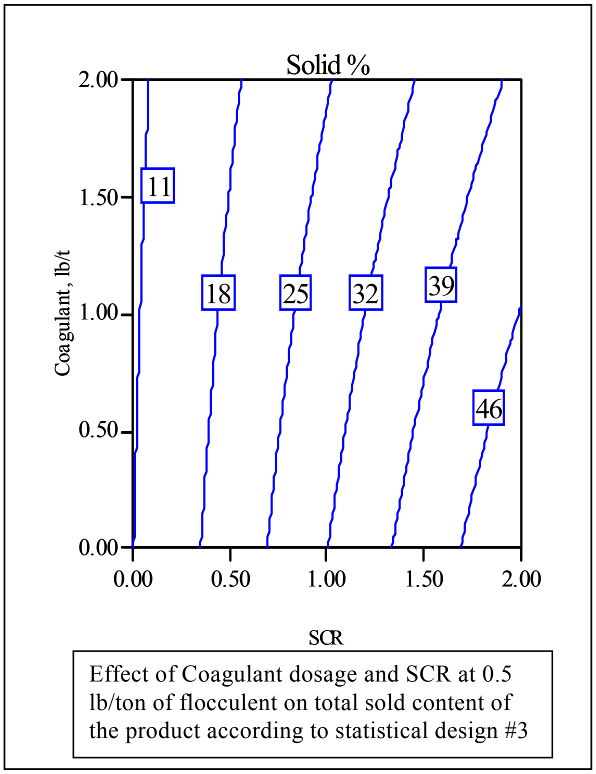


Figure 9. Effect of Coagulant Dosage and SCR at 0.5 Lb./Ton of Flocculant on Total Solids Content in the Product from the Third Design.

Consolidation in Disposal Pits

In addition to the above statistical designs, two test pits (4 × 4 × 4 feet) were filled with product. One was half full of water before pumping the product under water to test the disintegration of the flocs and to simulate filling a mine cut containing water. The second pit was dry and the product was tested by coring it at different times to analyze for consolidation and segregation of the sand (see Figure 10). The results indicate that the product may be deposited under water without segregation, as indicated by visual observation. Interestingly, the produced mixture can dewater in the dug-out area to a level that could have a load-bearing capacity (after 72 hours of consolidation), as shown in Figure10. The analysis of the core samples taken from this pit (also shown in Figure 10) suggests a rapid dewatering.

Core sample from test pits

Initially
Solid % = 40.12 %; initial SCR = 2.6 %
Initial bed height = 3 ft 1.5 in
After 48 hrs
Solid % = 60.1%; SCR at 4 inches from the top of the core = 2.4
SCR at 4 inches from the bottom of the core= 2.8
Decrease in height after 48 hrs = 3.25 in
(Decrease in height after 24 hrs = 2 in.)

Figure 10. Clay/Sand Mixture in Test Pit after Three Days of Disposal (Dewatered Clays Show Some Load-Bearing Capacity).

Lessons Learned

Based on our observations during pilot plant operations, we can list the following suggestions for improvements in both the design and operation of the pilot plant and full plant operations of this process:

- Provide easy and reliable means to measure flow rates and solids contents, especially incoming clay feed, cyclone feed and overflow.
- Use rakes in the clarifier to smooth the underflow solids content and prevent solids build-up in the clarifier. In actual practice, the clarifier could be a dug-out area with proper design (length, width, bottom slope, etc.)
- Use rakes in the clarifying cone for the cyclone underflow to provide uniform product quality. In actual plant operations, this cone could be replaced by the mine cut (disposal area) provided the water is removed from the surface of the settled mix
- If further dewatering is required, use a larger screen area. This could be calculated based on the product flow rate.
- Use separate (not split) feeding points for reagents
- Use a built feeder for sand rather than a screw feeder
- Use strainers under the sand and clay feeding points to prevent rocks and larger objects from plugging the pump and consequently changing the pressure drop

- If possible, use positive displacement pumps for both cyclone feed and product disposal
- Test old newsprint instead of sawdust
- A preliminary cost analysis is needed to check the economic feasibility of the process

This analysis was conducted by Penn Pro, Inc., and is given below.

PRELIMINARY COST ANALYSIS

A preliminary cost analysis conducted by Penn Pro suggested that the FIPR/DIPR cost could range between $0.95 and $1.60 per ton of phosphatic clay. Two tables are given below with cost estimates for current clay pond construction (Table 6) coupled with the costs of clay transport to the pond and the subsequent reclamation of the pond. Table 7 shows these costs as a unit cost per ton of clay with an optimum view of the FIPR/DIPR process. Current experience of earth-moving costs and discussion with several project managers about their actual costs are included as input.

Table 6. Biography of a Clay Pond.

Basis: 1 sq. mi., 30' deep, PV cost, 4 yrs. active over 10 yrs.
3:1 outside, 2:1 inside, 20' crest, $5/yd. soil moved, 10% engr.
Holds 28,964,542 tons of clay at 25' deep and 40% solids.
Clustered with 2-7 other clay ponds.

Cost Element	M Dollars
1. Pond construction, engineering, project mgt.	9,535
2. Operation of pond only. Oprs. sup., rd./dam maint., mowing, op. inspect., PE inspect.	1,750
3. Reclamation at $5000/acre. Clearing, ditching, dewatering, level dams, remove spillways, rock new outlets, planting, 10% engr.	3,200
4. Contingency at 10%	1,448
Total	15,933

$15,933,000/28,964,542 clay tons = $0.550 per ton

This excludes clay mining and plant equipment costs except for pumps.
These costs are felt to be common to all systems.

Table 7. Cost Estimates of Clay Disposal According to Conventional and FIPR/DIPR Processes.

Basis: Optimum view of FIPR/DIPR versus a realistic view
of current conventional clay settling.

Conventional Clay Settling	$/Ton Clay
A. Pond construction, operation, reclamation 10% contingency	0.550
B. Pipe—2 mi., 48” SDR17, 4'/sec., purchase/install	0.115
C. Pump(s) and controls, 10 yrs.	0.039
D. Power, 3% solids, $0.05/kwh	0.215
E. Maintenance	0.005
Total	0.924

$0.924 × 28,964,542 tons = $26,763,237 for 4 yrs. active over 10 yrs. time.

Optimum FIPR/DIPR	First	Revised	Lowest
A. Reclamation being done. A pond. Operation?	0.050	0.100	0.050
B. Pipe at 33% and 50% of above	0.041	0.061	0.041
C. Additional clay facility, $5 MM, $10 MM	0.172	0.355	0.172
D. Power at 10%, 20%	0.022	0.050	0.022
E. Floc, coagulant, $1/lb., 1.0 lb./t., 0.5 lb./t.	1.250	0.600	0.600
F. Fiber	0.050	0.100	0.050
G. Maintenance at 3% of $5 MM and $10 MM	0.005	0.010	0.005
Totals	1.590	1.276	0.940

First: $1.590 × 28,964,542 tons = $46,503,621
Revised: $1.276 × 28,964,542 tons = $36,958,756
Lowest: $0.94 × 28,964,542 tons = $27,226,669

On the basis of the lessons learned and the preliminary cost analysis, modifications to the pilot plant were proposed and a second phase was funded by FIPR. Details of the activities conducted in the second phase is given in Part II of this report and the flow diagram of the modified pilot plant is given in Figures I-11 and I-12.

PHASE II: PILOT PLANT TESTING

The objective of running the modified pilot plant was to produce dewatered mixtures to be tested for consolidation rate, permeability, and load-bearing capacity. Products included clay/fiber/sand mixture at 1:1 SCR (sand/clay ratio), clay/fiber mixture, and clay/sand mixture at 1:1 SCR. In addition, data about the operating parameters such as reagents’ dosages, fiber %, flow rates; material balances, etc. were collected. All data were analyzed and evaluated in terms of technological and economic performance as well as different clay disposal techniques that can be used to minimize clay settling areas. Special attention was paid to the evaluation of the load-bearing capacity of the produced mixtures. The following is a summary of the activities that took place to achieve the project goals.

Activities Done by Met Pro Supply and Penn Pro, Inc.

Met Pro Supply

Met Pro Supply completed the modifications and placement of the new equipment in the sand/clay mix pilot plant at the Mosaic South Ft. Meade Plant according to the flow diagrams given in Figures 11a and 11b. The additions and/ or modifications included a new clay settling tank, pinch valves with automatic controllers on the clay supply line and the large clarifier underflow, a manually controlled pinch valve on the small clarifier underflow, a Worthington pump on the clay supply line, a new cyclone feed sump, a sand feeder hopper, conveyor belt and vibrator, a piping and valve system for the plant, a clay pick-up device on the incoming clay line, a UHMW liner system in the large and small clarifiers, a "rake" in the large clarifier with VFD controls, a Moyno pump for the product discharge, a shredder for the pulp and shredded and supplied 2000 pounds of newspaper print for pulp, two 400 gallon steel tanks for pulp preparation and storage, rental equipment including a Bobcat front-end loader, diaphragm pumps, and an operator's control shack, equipment and labor to move and install the new flocculation supplier equipment to the job site, manpower to remove previously used equipment, modify and installed all new mechanical equipment, assistance on the installation and maintenance of the instrumentation, and manpower to maintain and operate the pilot plant, during which the three columns were filled and the design experiments were run.

Penn Pro, Inc.

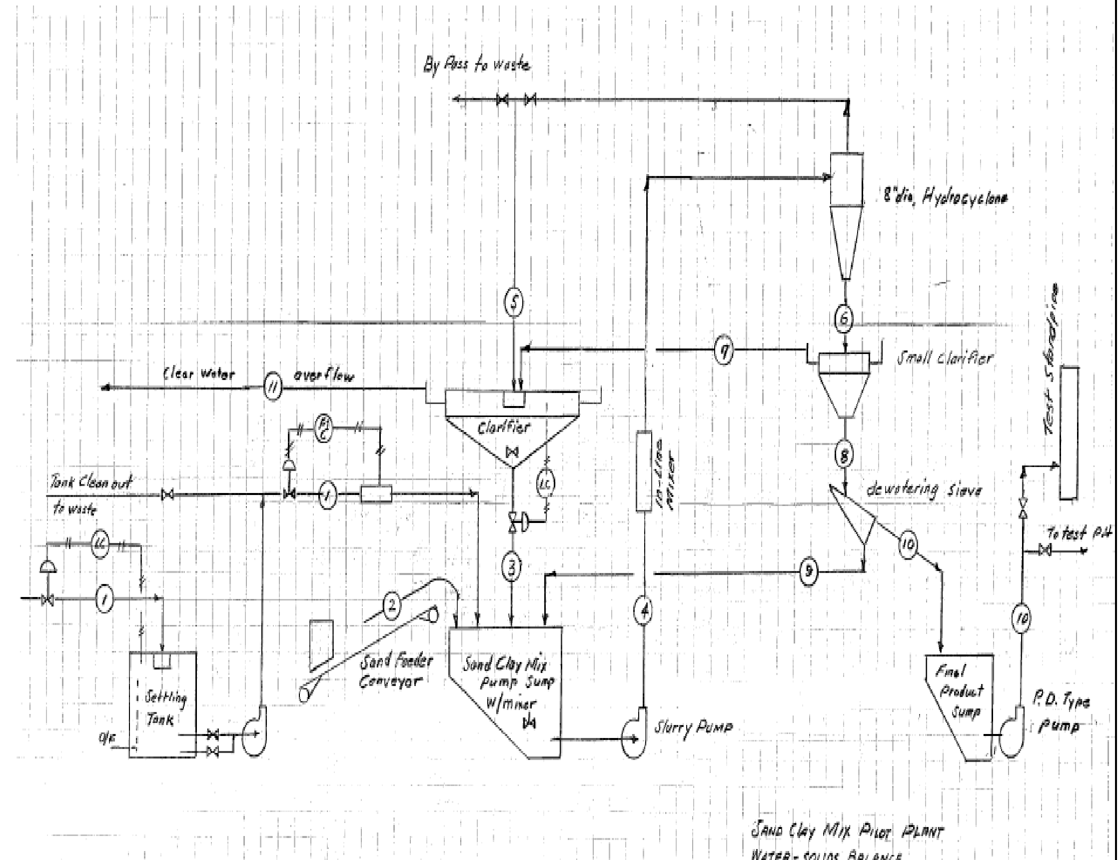
Supply Instrumentation. This included the feed mass flow, clarifier level control, separator level control, power supply filter and product pump ammeter, as listed below. Penn Pro's master electrician/programmer assisted with the rest of the installation. After detailed discussion for instrument and electric design, it was found to be more economical to have a small DCS system instead of individual PID controllers. The four loops were installed from design loop sheets, not single-line drawings. This provided computer block diagram graphics to a laptop with much greater flexibility and control. All instrument wiring was in cable trays, not conduit, and not "Esso" cord per IMSHA requirements. The following is a list of the instrumentation:

- Feed mass flow Coriolis meter (mass flow and density). Flow and density on PLC. East slab location.
- Clarifier level control including sensor on PLC
- Underflow rec level control including sensor on PLC
- Power filter for electrical supply, miscellaneous transformers

- Programmable logic controller, AB1756 or Motorola
- Feed control loop
- Laptop, 512 meg ram with XP Pro or Windows 2000
- Programming, graphics, engineering, design for I&A with five control loops
- Instrument maintenance for operation

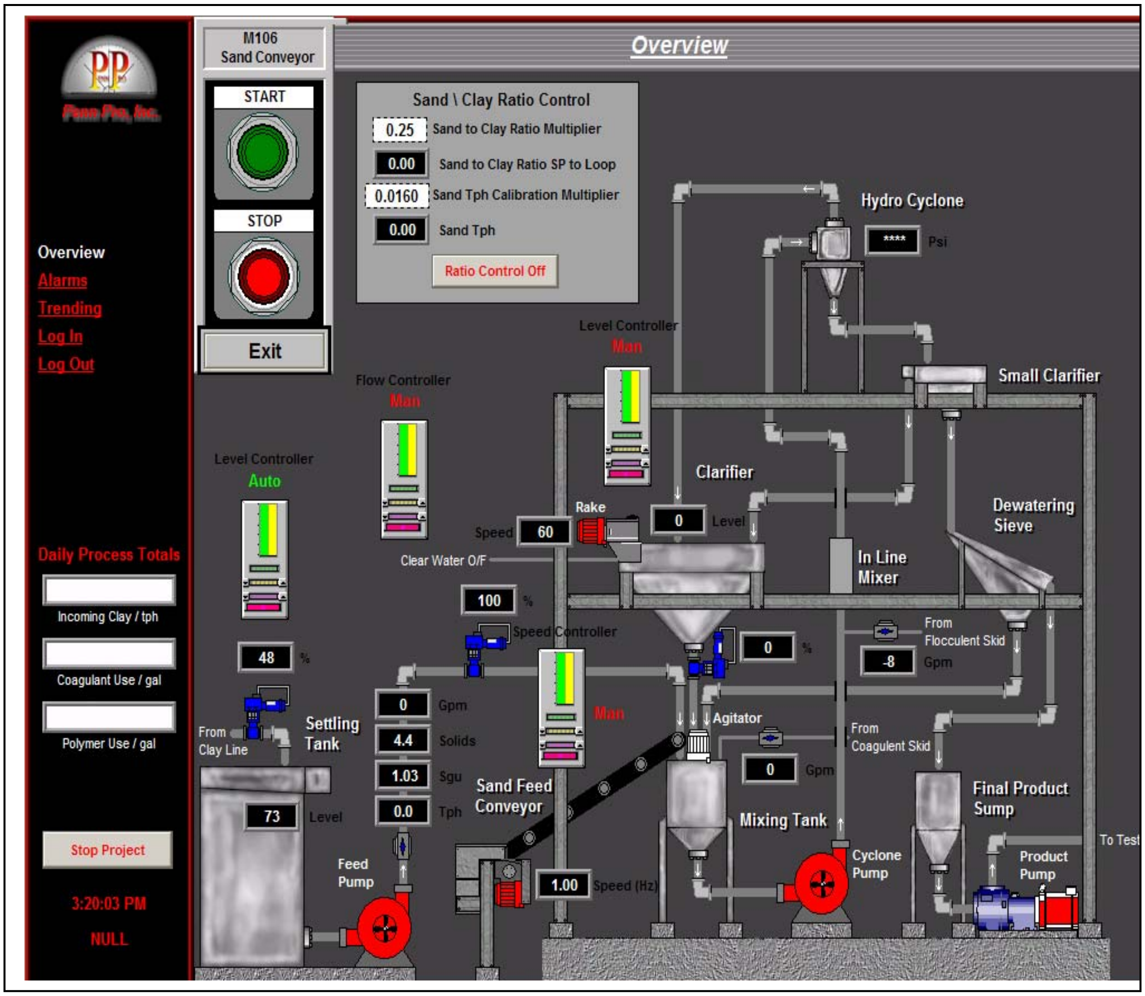
Engineering, Operation and Maintenance. This was done to analyze run results and to furnish on-site engineering assistance on startup and operation.

Determination of Technical and Economic Feasibility. Penn Pro conducted the economic analysis of using FIPR/DIPR process as a reclamation technique to minimize the clay settling areas. The results are summarized after the geotechnical testing.



Line	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪
T.P.H.	1.75	3.5	0.25	5.50	0.25	5.25	0	5.25	0	5.25	0
% Solids	4	85	16	11	1	31	0	29	0	28	0
GPM Slurry	170	8	5	185	126	59	0	56	0	54	0
GPM Water	167	2.5	4.40	176	125	51	3	48	2	46	124
S.G.	1.03	2.10	1.12	1.07	1.00	1.25	1.00	1.24	1.00	1.24	1.00

Figure 11a. Conceptual Flow Diagram of the Modified FIPR/DIPR Phase II Pilot Plant.



Sand \ Clay Ratio Control

0.25 Sand to Clay Ratio Multiplier

0.00 Sand to Clay Ratio SP to Loop

0.0160 Sand Tph Calibration Multiplier

0.00 Sand Tph

Figure 11b. Flow Diagram of the Modified FIPR/DIPR Phase II Pilot Plant with Controller Identified.

Pilot Plant Operation

Problems in getting proper feed clays resulted in a few months' delay of the project that also resulted in consumption of budget since operators were on site all the time ready to operate. Such delays resulted in SNF's (a polymer supplier) withdrawal from the project activities. Thus, another supplier (Hengju) of China was called and they brought their equipment and polymers on site after a few weeks of further delays. The pilot plant was ready after all modifications were done by Met Pro Supply and instrumentation was added by Penn Pro. Then the pilot plant was run and the three stand pipes were filled with clay/pulp, clay/sand mixture, and clay/sand/pulp mixture. Samples were collected during filling and analyzed for sand/clay ration, % solids, and fiber content. Samples were also sent for consolidation testing by BCI and the results are reported below.

GEOTECHNICAL TESTING AND EVALUATION OF FIPR/DIPR PROCESS FIELD DEMONSTRATION/EVALUATION PHASE II

SUMMARY

This part of the report describes the Phase 2 field activities and laboratory testing performed by BCI Engineers & Scientists, Inc. (BCI) to assist in a field demonstration and evaluation of a rapid clay dewatering and consolidation process developed by Dr. Hassan El-Shall, University of Florida, Principal Investigator for the project. The field-testing utilized equipment designed and constructed by a research team that, in addition to the University of Florida and BCI, included Met Pro Supply, Inc., JRS, Inc., and Penn Pro Engineering & Technical Services, Inc. The pilot plant was located at Mosaic's South Fort Meade Mine, which supplied the waste clays and tailings sand utilized in the test.

The process involves flocculation and dewatering of waste clays from a phosphate washer/flotation plant using high molecular weight organic polymers (dual polymer system, involving anionic and cationic polymers), mixing the clays with organic fiber (such as shredded paper pulp), and/or dewatered tailings sand, and pumping the high-solids mixture to an impounded disposal site for further dewatering and consolidation.

The primary goals of the research project were to demonstrate at pilot-plant scale the technical and economic feasibility of the FIPR/DIPR process as a practical means for reducing clay settling areas, and to demonstrate that the reclaimed disposal sites would have higher economic value and be more suitable load-bearing land than conventional reclaimed clay settling areas.

Phase 1 of the project, completed in 2005 and reported later in Part I of this report, involved design of the plant system, testing and optimization of flocculants, evaluation of various waste fiber materials, and testing of various clay and sand dewatering and mixing alternatives. During initial testing of the equipment, various design and operational problems were encountered and adjustments made. After several trial runs, the pilot plant was shut down and the research team developed a list of modifications and improvements. Phase 2 of the project involved implementation of these modifications and improvements, and the additional operations and testing reported herein.

BCI's primary assignments in the project involved sampling and testing of the clay mix products produced by the plant to determine settling and consolidation properties, and to evaluate the mixtures for ultimate load-bearing capability.

The Phase 2 tasks completed by BCI included participating in the planning of modifications to the pilot plant and in field activities to implement the changes. Three pipe columns consisting of 25-foot lengths of HDPE pipe were erected adjacent to the plant, and were filled with clay mix products from the plant. The columns provided a height of fill representative of a field disposal situation, allowing monitoring of the settling and self-weight consolidation that occurs in plant-scale operations. The columns

were fitted with valve ports for sampling and monitoring pore water pressures at various times.

During operation of the pilot plant, the pipe columns were filled with three different products: clay/fiber mix, clay/sand mix, and clay/sand/fiber mix. Grab samples of each mix were taken as the pipes were being filled. Samples of the raw untreated clay being fed to the plant were also taken. The samples were taken to the BCI laboratory for geotechnical testing and analysis, as described herein.

Following filling of each pipe column, periodic measurements were taken to determine the height of the consolidating clay mix. Pore pressure measurements were also taken to determine the percentage consolidation of the mix. As consolidation approached completion, samples were taken from sample ports on the columns.

The samples returned to the laboratory were tested for moisture (solids) content and percent sand-size material (using a No. 140 sieve, as is customary in the industry). Selected samples were tested for plasticity (Atterberg Limits), organic (fiber) content, and settling tests. Composited samples from each column were mixed and tested in a constant rate of strain consolidation (CRSC) test apparatus. After consolidation, shear strength of the samples was measured using direct simple shear (DSS) equipment. The shear strength results were used to calculate ultimate and allowable bearing capacities for the three mixtures.

The laboratory and field test results and data were analyzed and evaluated to compare consolidation and strength behavior among the three clay mix products. Consolidation parameters were determined based on the column tests and CRSC tests, using the computer program SLURRY, which was developed for FIPR under a research grant to Ardaman & Associates in 1983. The consolidation parameters can be used to predict consolidation rates and final solids contents for various mining and reclamation scenarios. In this manner, mining companies can make economic analyses to compare the costs of implementing the FIPR/DIPR process with their current costs of clay disposal and land reclamation.

METHODOLOGY

BCI's involvement included installation of three pipe columns that were subsequently filled with clay mix products from the plant. The pipe columns consisted of 25-foot lengths of HDPE pipe that were erected adjacent to the pilot plant, and were filled with clay mix products from the plant. The columns provided a height of fill representative of a field disposal situation, allowing monitoring of the settling and self-weight consolidation that occurs in plant-scale operations. The columns were fitted with valve ports for sampling and monitoring pore water pressures at various times.

During operation of the pilot plant, the pipe columns were filled with three different products: clay/fiber mix, clay/sand mix, and clay/sand/fiber mix. Grab samples of each mix were taken as the pipes were being filled. Samples of the raw untreated clay being fed to the plant were also taken. The samples were taken to the BCI laboratory for

physical testing and analysis. All of the tests were run in accordance with ASTM standards, where they exist, and with industry standards as applicable.

Following filling of each pipe column, periodic measurements were taken to determine the height of the consolidating clay mix. Pore pressure measurements were also taken to determine the percentage consolidation of the mix. As consolidation approached completion, samples were taken from sample ports on the columns. These samples were also taken to the BCI laboratory for physical testing and analysis.

The laboratory and field test results and data were analyzed and evaluated to compare settling, consolidation and strength behavior among the three clay mix products. Consolidation parameters were determined in three ways: based on plasticity (Atterberg Limits), the observed rates of settling and consolidation in the column tests, and data collected in laboratory CRSC tests.

The consolidation properties of clay slurries are directly related to plasticity, as shown by Carrier (Carrier and others 1981, Carrier and Beckman 1984), with higher-plasticity clays being more compressible and requiring longer periods of time to settle and consolidate. The work by Carrier and subsequent research for FIPR by Ardaman & Associates, Inc. (1983a) confirmed this relationship in quantitative terms that allow prediction of field behavior based on simple laboratory classification tests.

Using the computer program SLURRY, which was developed for FIPR under a research grant to Ardaman & Associates in 1983 (Wissa and others 1983b), the consolidation results from each of the tests—plasticity index, pipe column, and CRSC—were compared for each of the clay mixes.

The consolidation parameters can be used to predict rates of settlement and final solids contents for various mining and reclamation scenarios. In this manner, mining companies can make economic analyses to compare the costs of implementing the FIPR/DIPR process with their current costs of clay disposal and land reclamation.

The bearing capacity of foundations placed on soils depends on the shear strength of the material. In order to estimate the bearing capacity of the clay mixes, shear strengths were measured using a direct simple shear (DSS) test apparatus. The tests were run in accordance with ASTM D6528 (Standard Test Method for Consolidated Undrained Direct Simple Shear Testing of Cohesive Soils). The DSS test generates a fairly homogeneous state of shear stress throughout the specimen, and models field loading conditions more closely than other test systems such as triaxial tests.

The shear tests were run by transferring consolidated specimens from the CRSC test to the DSS apparatus, and consolidating them to vertical effective stresses ranging from 1500 lbs/sq. ft. to 6000 lbs/sq. ft. In this manner, both undrained shear strength as a function of effective stress, and effective stress friction angle, φ', and cohesion, c', can be determined.

The results of the DSS tests were used to estimate ultimate and allowable bearing capacity for both undrained and drained conditions, as a function of solids content. The undrained (φ= 0) case has a lower allowable bearing capacity, and is considered to be the more valid failure mode for a clay material.

FIELD ACTIVITIES

Introduction

During June 2006, upgrading of the pre-existing FIPR/DIPR sand/clay mix and dewatering pilot plant began (Figure 12). The purpose was to resume treatment and sampling of South Fort Meade clays in the presence of pre-determined combinations of sand, paper pulp (fiber), and polymer. Plant preparation included the installation of various automatic controls, as well as a small conveyor structure to introduce sand to the system at the desired rate with reasonable stability. A fiber-mixing vessel and a polymer addition system were installed, and a pipe launder was added to direct plant product (combinations of flocculated sand/clay/fiber mix) to a positive-displacement pump for transfer to test areas.

Figure 12. Upgrading of the Pre-Existing FIPR/DIPR Sand/Clay Mix and Dewatering Pilot Plant.

To accommodate measurements of rates of settling and consolidation, three 25-foot sections of 36-inch diameter HDPE pipes were erected side-by-side near the pilot plant and supported vertically. These pipe columns were intended to accept treated clay products from the pilot plant, where settling and consolidation properties would be measured after filling. A 50-foot diameter, 12-foot deep test pit was also constructed with the intent to observe the mixed clays consolidation behavior in a larger clay deposition environment.

Site Preparation

Column Description

Three 25-foot lengths of HDPE pipe were used as settling and self-weight consolidation test columns for the project (Figure 13). Two of the columns were fitted with three three-inch diameter valved sampling ports, and the third was a pre-existing column previously fitted with four sampling ports.

Two columns were then fitted with three two-inch valved ports with porous probes intended to act as piezometers. These probes were covered with filter cloth to prohibit clay infiltration. The third pre-existing column was previously fitted with two piezometer ports. Clear tubing was attached to a nipple on each two-inch port and extended to the top of each column.

These piezometers would indicate pore-pressure dissipation with time as settling occurred. The goal was to use measured settlement data, in conjunction with subsequent laboratory test data to evaluate consolidation behavior as a function of the various flocculated clay/sand/fiber combinations.

Figure 13. Consolidation Test Column.

Scaffolding (see Figure 14) was erected along the length of the three columns to provide access for measuring water and clay levels, and later, for sampling the clay column from top to bottom.

Figure 14. Scaffolding to Provide Access for Measurements of Water and Clay Levels.

The flocculated clay mixtures flowed by gravity from the pilot plant down a pipe into a small conical positive displacement pump feed hopper. The pump discharge hose connected to a 90-degree transition 'T,' feeding a vertical run of PVC pipe, which discharged into each column.

Test Pit

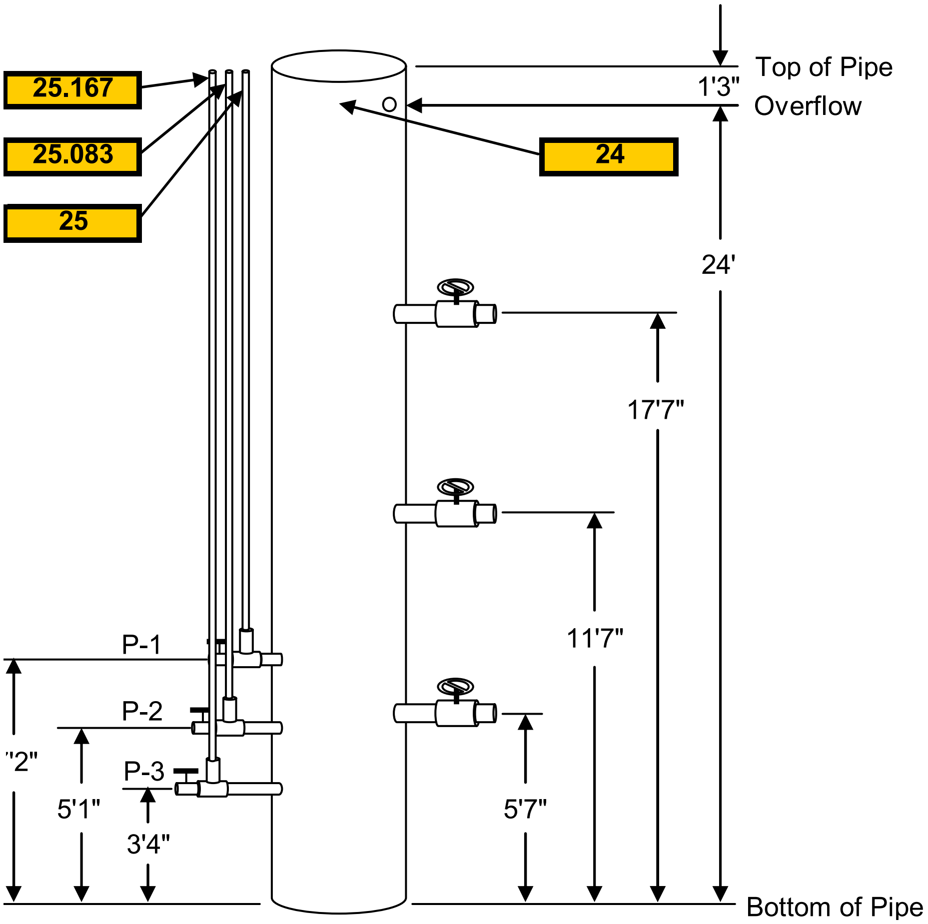
A below-grade pit was constructed with the intent to simulate a more representative deposition scenario (see Figure 15). The pit was approximately 50 feet in diameter and 12 feet deep with an overflow control point and ditch two feet below grade, located about 30 yards from the pilot plant. The test pit was not used due to extended delays throughout the project.

Figure 15. Test Pit.

Column Filling

Column 1 (South)

Numerous equipment and operational delays hindered completion of the pilot plant and pumping system. Further, numerous operational problems experienced by the phosphate beneficiation plant donating the clays caused extended delays. After weeks of delays, the first column was filled on October 5, 2006. The following graphic (Figure 16) shows the column as filled initially. This column was filled with a flocculated clay/fiber mix.

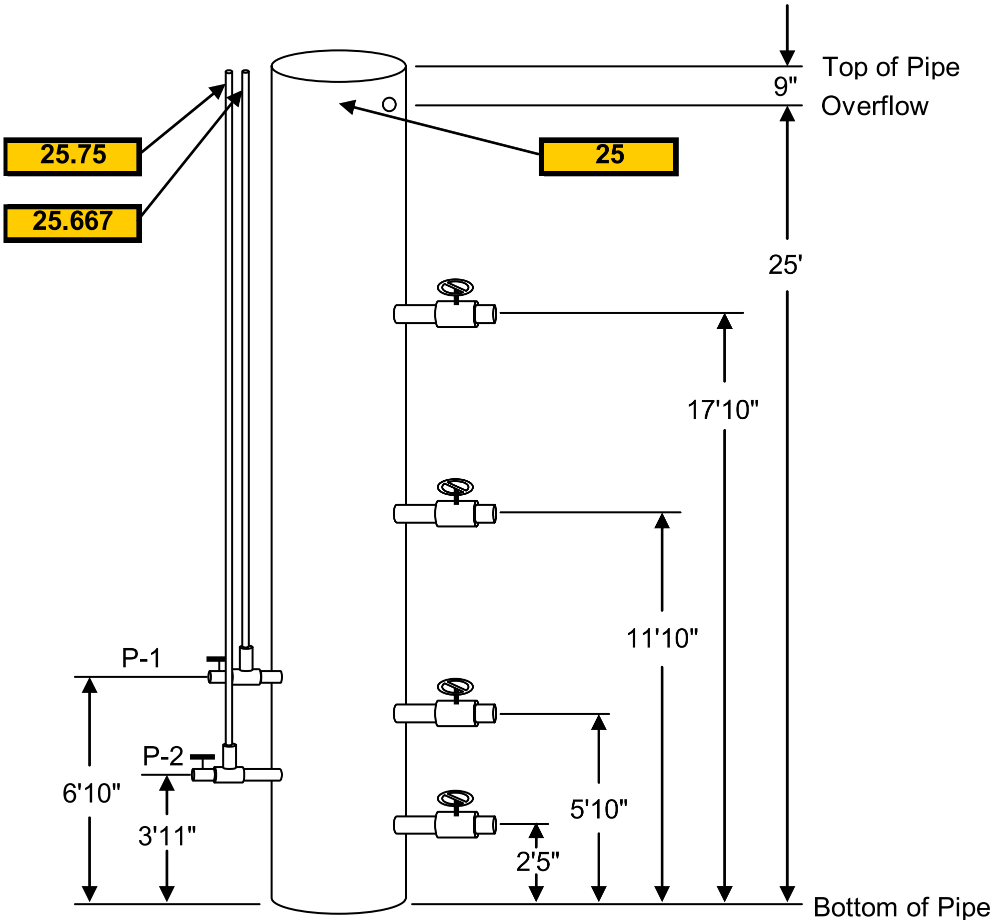


South Column Initial Fill - Clay/Pulp
10/05/06 2;00 PM - 3:50 PM

Figure 16. Column 1 (South).

Column 2 (Center)

Host plant operational delays resumed and the second column filling was not commenced until November 20, 2006. During filling, however, clay delivery from the host plant was interrupted and filling was halted. The following afternoon the decision was made to resume filling the column until full. This resulted in a degree of 'stage-filling' but it was felt that since the duration between initial and second filling was less than 24 hours the impact would be negligible. The following graphic (Figure 17) shows the column as filled initially. This column was filled with a flocculated sand/clay mix.

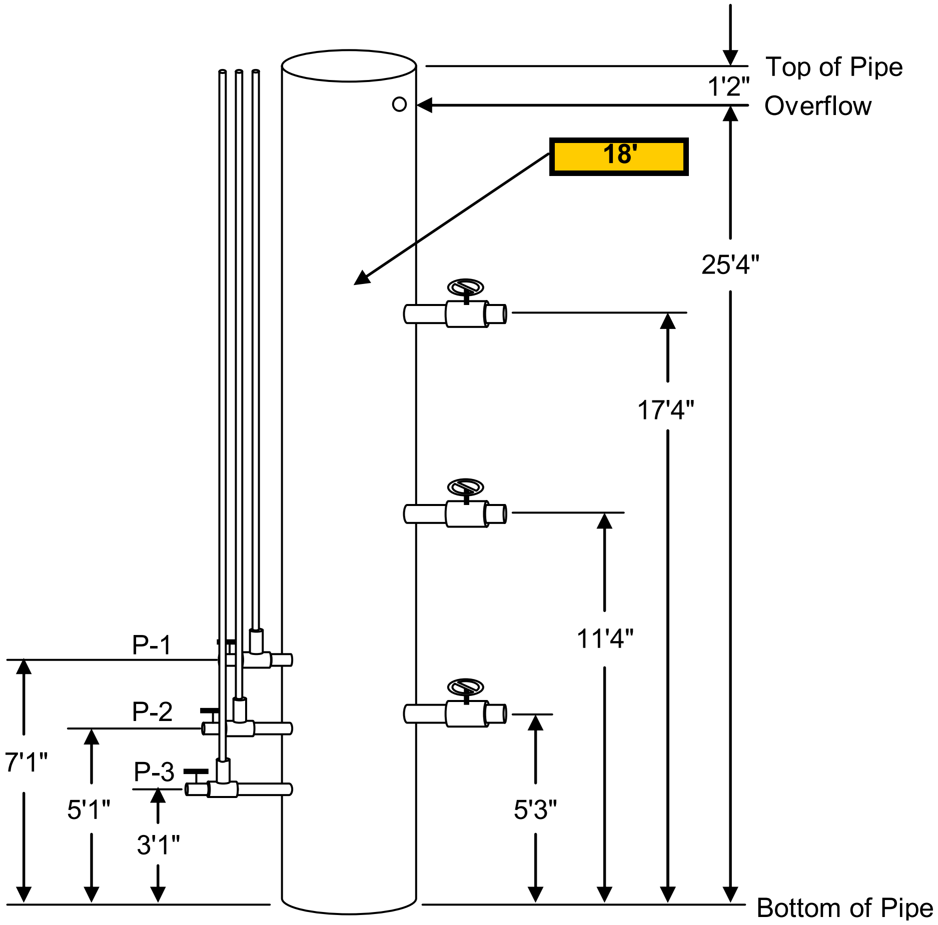


Middle Column Initial Fill - Sand/Clay
11/20/06 6:00 PM - 7:45 PM
11/21/06 3:30 PM - 5:30 PM
Measured 11/27/06 Prior to Decanting

Figure 17. Column 2 (Center).

Column 3 (North)

The final column was filled on November 29, 2006. However, with about six feet remaining to complete filling, the bottom flange on the column failed. This allowed a leak to develop at the bottom of the column. Attempts to seal this leak were successful for a period, but water began to drain through a few weeks later. Additional water was placed in the column to keep the clay surface hydrated, but drainage continued. Several more unsuccessful attempts to place a seal followed and the effort was abandoned. Unable to keep water in the column we let the clays continue to drain and dry. The following graphic (Figure 18) shows the column as filled initially. This column was filled with a flocculated sand/clay/fiber mix.



North Column Initial Fill - Sand/Clay/Pulp
11/29/06 3:50 PM - 7:05 PM

Note - Bottom of Column Failed During Filling at About 18' from the Bottom - No Other Measurements Taken. Bottom Sealed Overnight.

Figure 18. Column 3 (North).

Column Sampling

As each column was filled, samples were taken at approximately ten-minute intervals. Each sample was used to fill a 500-ml. bottle, which was labeled and sealed, and the remainder of the one-gallon sample was added to a column composite. As a result, each column had an associated ten-gallon composite and ten 500-ml. bottles of sample representing that column.

In addition to the pilot plant treated clays, raw clays from the host beneficiation plant to the pilot process were sampled as five-gallon composites during column filling. Raw clays from the initial fillings of Columns 2 and 3, as well as bottle samples from Columns 1, 2 and 3 were analyzed for percent solids and sand/clay ratio. A sample from the initial fill composite of Column 3 was also analyzed for solids content for comparison to the bottle sample. These are shown in Tables 8, 11 and 14, respectively. Additional solids content data are shown in each of these tables, dated, and described accordingly.

During the settling phase of the column testing, piezometer-tubing water levels were routinely recorded and are shown in Tables 9, 12, and 15. These levels were monitored until the end of March 2007.

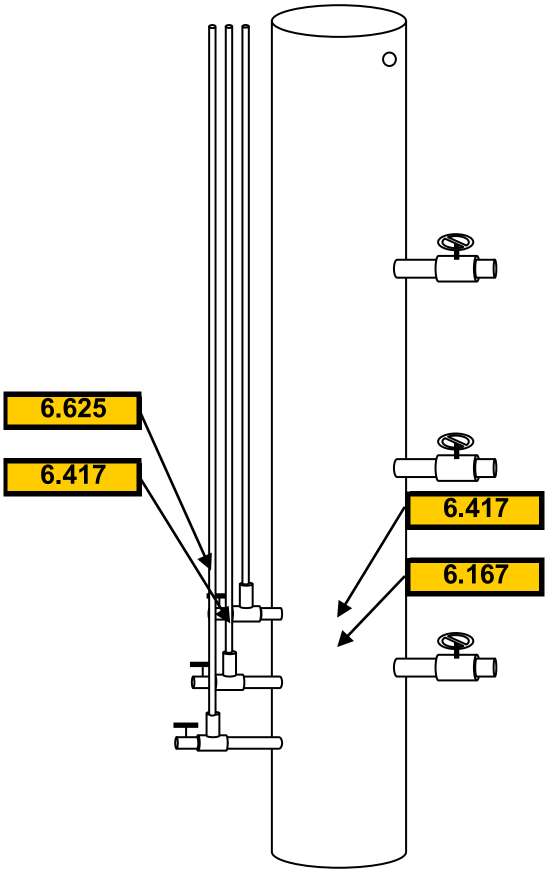
The observed pore pressure dissipation indicated that Column 1 was ready to sample about mid-February 2007, and Columns 2 and 3 were ready during the third week of March 2007. Sampling was accomplished by drilling one-inch holes in the side of each column. These holes were drilled at regular intervals beginning near the bottom and moving up the column. A sample was extracted from each hole, representing the material at that elevation. After sampling, the holes were plugged.

Samples collected at each point were placed in separate 500 ml bottles and labeled accordingly. Column 1 was sampled twice to complete a missing sample point and Columns 2 and 3 were complete with one sampling event. Column 1 samples were analyzed for solids content, and samples from Columns 2 and 3 were analyzed for solids content and sand/clay ratio. The data are shown in Tables 10, 13, and 16.

Data Collection

Column 1 (South)

The following graphic (Figure 19) shows the column and clay configuration as the last piezometer reading was made on Column 1.



South Column - Clay/Pulp
Measured 03/29/07

Initial Fill - Clay/Pulp
10/05/06 2:00 PM - 3:50 PM

Figure 19. Column 1 (South) Configuration at Final Piezometer Reading.

Table 8. Column 1 Initial Fill Solids Data.

Date	Sample	Solids Content (%)
N/A	Raw Plant Clay	Not Analyzed
10/05/06	Initial Fill Composite from Bottles	8.0
11/29/06	5’7” from Bottom of Column	19.9
12/15/06	5’7” from Bottom of Column	19.5

Table 9. Column 1 Piezometer, Water and Clay Levels.

Date	Measured Values (Feet from Bottom of Column)				
	Piezometers			Water	Clay
	P-3	P-2	P-1		
10/05/06	25.167	25.083	25.000	24.000	
10/23/06	22.667	22.583	22.500	22.333	
11/02/06	12.167	11.917	11.625	11.458	
11/10/06	11.583	11.532	11.490	11.417	
11/15/06	11.708	11.583	11.458	11.417	7.583
11/17/06	11.510	11.489	11.458	11.458	7.583
11/27/06	11.583	11.479	11.375	11.333	7.333
11/28/06	11.396	11.396	11.354	11.333	7.333
11/29/06	11.354	11.354	11.354	11.333	7.167
12/01/06	11.375	11.333	11.292	11.208	7.000
12/08/06	11.270	11.250	11.208	11.292	7.000
12/15/06	11.437	11.416	11.375	11.375	7.104
12/22/06	11.291	11.271	11.250	11.250	6.833
1/04/07	11.229	11.218	11.187	11.220	6.513
1/19/07	11.055	11.010	10.935	11.050	6.600
2/05/07	**11.04***	**11.29***	**11.00***	10.960	6.367
2/26/07	**	6.767		6.933	6.103
3/29/07	6.625	6.417		6.417	6.167

*Disturbed due to sampling.

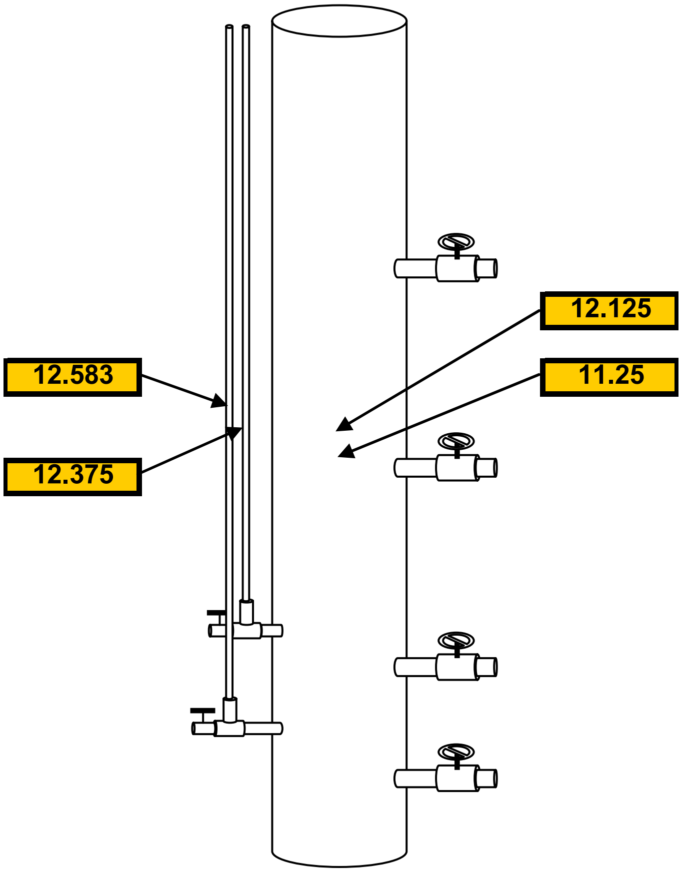
**Seal at valve attach point broken – attempted to re-seal but level had not recovered.

Table 10. Column 1 Column Solids Profile.

Column	Solids Content (%)		
	2/15/07	2/26/07	3/29/07
Bottom + 5’	20.3	19.9	
Bottom + 4’	22.3	22.5	
Bottom + 3’	25.5	24.7	
Bottom + 2’	23.7	26.4	
Bottom + 1’		30.8	
Bottom	37.6		
Column Composite			22.0

Column 2 (Center)

The following graphic (Figure 20) shows the column and clay configuration as the last piezometer reading was made on Column 2.



Middle Column - Sand/Clay
Measured 03/29/07

Middle Column Initial Fill - Sand/Clay
11/20/06 6:00 PM - 7:45 PM
11/21/06 3:30 PM - 5:30 PM

Figure 20. Column 2 (Center) Configuration at Final Piezometer Reading.

Table 11. Column 2 Initial Fill Solids Data.

Date	Sample	Solids Content (%)	Sand/Clay Ratio
11/21/06	Raw Plant Clay	6.4	N/A
11/21/06	Initial Fill Composite from Bottles	12.0	1.26 : 1
11/21/06	Decanted Bucket Composite	31.5	1.84 : 1
11/29/06	11’10” from Bottom of Column	26.9	0.77 : 1
11/29/06	2’5” from Bottom of Column	30.4	1.00 : 1
12/15/06	11’10” from Bottom of Column	*49.0	
12/15/06	2’5” from Bottom of Column	31.3	
1/19/07	11’10” from Bottom of Column	**39.8	
1/19/07	2’5” from Bottom of Column	35.6	

* Appears high

** Now top of clay – appears high

Table 12. Column 2 Piezometer, Water and Clay Levels.

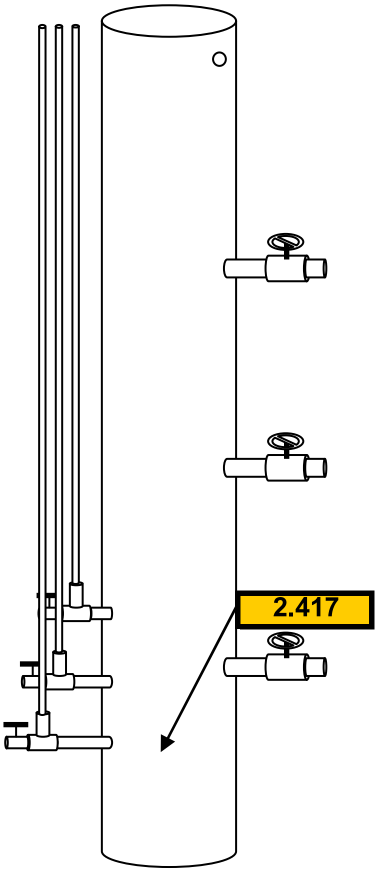
Date	Measured Values (Feet from Bottom of Column)			
	Piezometers		Water	Clay
	P-2	P-1		
11/21/2006	25.750	25.667	25.000	
11/27/2006	19.625	18.723	17.792	14.008
11/28/2006	19.291	18.625	17.708	13.833
11/29/2006	19.167	18.500	17.708	13.750
12/1/2006	19.292	18.500	17.625	13.417
12/8/2006	18.791	18.166	17.667	13.042
12/15/2006	18.958	18.291	17.730	12.583
12/22/2006	13.688	12.958	12.550	12.209
1/4/2007	13.479	12.875	12.630	11.875
1/19/2007	13.618	12.798	12.630	11.450
2/5/2007	13.000	12.625	12.670	11.458
2/26/2007	13.133	12.733	12.483	10.933
3/29/2007	12.583	12.375	12.125	11.250

Table 13. Column 2 Column Solids Profile.

Column	3/20/2007			
	% Solids	-140 Mesh	+140 Mesh	Sand:Clay
Bottom + 9’	21.6	67.0	33.0	0.49 : 1
Bottom + 8’	31.2	62.9	37.1	0.59 : 1
Bottom + 7’	44.8	39.8	60.2	1.51 : 1
Bottom + 6’	45.0	35.3	64.7	1.83 : 1
Bottom + 5’	48.7	33.4	66.6	1.99 : 1
Bottom + 4’	46.3	36.5	63.5	1.74 : 1
Bottom + 3’	51.1	30.0	70.0	2.33 : 1
Bottom + 2’	65.9	12.9	87.1	6.75 : 1
Column Composite	43.3	36.8	63.2	1.72 : 1

Column 3 (North)

The following graphic (Figure 21) shows the column and clay configuration as the last piezometer reading was made in Column 3.



North Column - Sand/Clay/Pulp
Measured 03/29/07

North Column Initial Fill - Sand/Clay/Pulp
11/29/06 3:50 PM - 7:05 PM

Note - Bottom of Column Failed During Filling at
About 18' from the Bottom - No Other
Measurements Taken. Bottom Sealed Overnight.

Figure 21. Column 3 (North) Configuration at Final Piezometer Reading.

Table 14. Column 3 Initial Fill Solids Data.

Date	Sample	Solids Content (%)	Sand/Clay Ratio
11/29/06	Raw Plant Clay	4.1	N/A
11/29/06	Initial Fill Composite from Bottles	17.3	1.68 : 1
11/29/06	Initial Fill Composite from Buckets	17.9	1.91 : 1
11/29/06	Decanted Bucket Composite	34.1	2.02 : 1

Table 15. Column 3 Piezometer, Water and Clay Levels.

Date	Measured Values (Feet from Bottom of Column)				
	Piezometers			Water	Clay
	P-3	P-2	P-1		
11/29/2006				18.000	
12/1/2006	11.458	11.333	11.333	11.208	6.417
12/8/2006	10.208	10.208	10.208	11.208	4.819
12/15/2006			5.250	5.125	4.750
12/22/2006			5.250	5.792	4.646
1/4/2007			3.883	5.160	4.558
1/19/2007				4.500	4.500
2/5/2007				4.710	4.500
2/26/2007					3.050
3/29/2007					2.417

Table 16. Column 3 Column Solids Profile.

Column	3/20/2007			
	% Solids	-140 Mesh	+140 Mesh	Sand:Clay
Bottom + 2.5’	22.3	96.4	3.6	0.04 : 1
Bottom + 2.0’	23.6	97.0	3.0	0.03 : 1
Bottom + 1.5’	26.6	94.6	5.4	0.06 : 1
Bottom + 1.0’	33.2	88.9	11.1	0.12 : 1
Bottom + 0.5’	56.6	41.3	58.7	1.42 : 1
Column Composite	32.5	83.7	16.3	0.20 : 1

LABORATORY TESTING

Introduction

Samples taken during the project were returned to the BCI laboratory in order to run classification tests and tests to determine geotechnical engineering properties, specifically settling rates, compressibility, permeability, and shear strength. The classification tests were performed according to applicable ASTM standards for each test. The engineering properties tests were performed using ASTM where applicable, as well as industry standard procedures, where applicable.

Description of Tests

The classification tests performed on the samples included Solids Content (water content) and Percent Fines (passing No. 140 sieve), Specific Gravity, Organic Content, and Atterberg Limits. Engineering properties testing included Settling Tests, Permeability Tests, Slurry Consolidation Tests, and Direct Simple Shear Strength tests.

Results of Laboratory Testing

Classification Tests

Solids content and percent passing No. 140 sieve were determined for all samples returned to the BCI laboratory. The relevant results are summarized in the preceding Section Field Activities, which describes the filling and subsequent sampling of the three clay mix pipe columns, and the laboratory test results. Other relevant classification tests are also presented.

Atterberg Limits

Atterberg Limits tests are used to evaluate the plasticity of cohesive soils. The engineering behavior of clay soils vary with their moisture (or solids) content, changing from a plastic (or moldable) solid to a viscous liquid with increasing amounts of water. The liquid limit (LL) of a soil is defined as the moisture content (expressed as weight of water divided by weight of dry solids) at which the clay will begin to behave as a liquid. Similarly, the plastic limit (PL) is the moisture content at which clay will begin to behave in a plastic manner. The plasticity index (PI) is calculated by subtracting the PL from the LL. The plasticity index represents the range of moisture content over which a clayey soil will be in a plastic state.

Bromwell and Carrier (1979) showed that Florida phosphatic clays have high plasticity values, generally much higher than other mining wastes and naturally occurring clays. The range of PI values for most clays is on the order of 10 to 100, whereas phosphatic clays range from about 60 to 200. The consolidation properties of clay slurries are directly related to plasticity, as shown by Carrier and coworkers (1981and 1983), Carrier and Beckman (1984), with higher plasticity clays being more compressible and requiring longer periods of time to settle and consolidate. The work by Carrier and subsequent research for FIPR by Ardaman & Associates, Inc. (1983) has confirmed this relationship in quantitative terms that allow prediction of field behavior based on simple laboratory classification tests.

In the FIPR/DIPR test program, a range of Atterberg Limits were measured. The composite clay samples for the column fills had PI values of 64, 125, and 82 for Columns 1, 2, and 3 respectively. Although this range is large, it indicates that the plasticity was generally in the lower range encountered for phosphatic clay.

Settling Tests

Settling tests were run on samples of clay material mixed with pulp. The samples were taken during filling of Column 1, as described earlier under "Field Activities." Each sample was thoroughly mixed and a 1,000 ml portion poured into a graduated cylinder. A sample was also taken for solids content and percent fines determination. The sample was again mixed by shaking the cylinder, and then allowed to settle quiescently. Readings of the slurry/supernatant interface were taken with time and recorded. When the settled slurry reached a constant level, generally 7 days, the clear water was decanted, and the final solids content determined.

The results of the settling tests are shown on Figure 22, and are tabulated in Table 17. The initial solids contents of the samples ranged from 6.8% to 9.0%. The percent passing the No. 140 sieve ranged from 90.5% to 99.4%. The samples generally reached equilibrium in seven days, much faster than typical unflocculated clays. Final settled solids contents ranged from 12.1% to 15.9%, which is within the range of settled solids contents for unflocculated clays.

Table 17. Settling Tests, Clay with Fiber.

Sample No.	Initial Solids Content (%)	% Passing No. 140 Sieve	Final Solids Content (%)
C-1-1	7.0	95.0	14.9
C-1-2	9.0	96.5	13.7
C-1-3	7.0	99.4	15.5
C-1-4	8.9	97.0	14.4
C-1-5	7.7	98.4	12.9
C-1-6	6.8	95.4	12.0
C-1-7	7.6	97.0	15.9
C-1-8	8.0	90.5	14.0
C-1-9	8.7	94.0	14.3
C-1-10	8.9	93.9	14.4

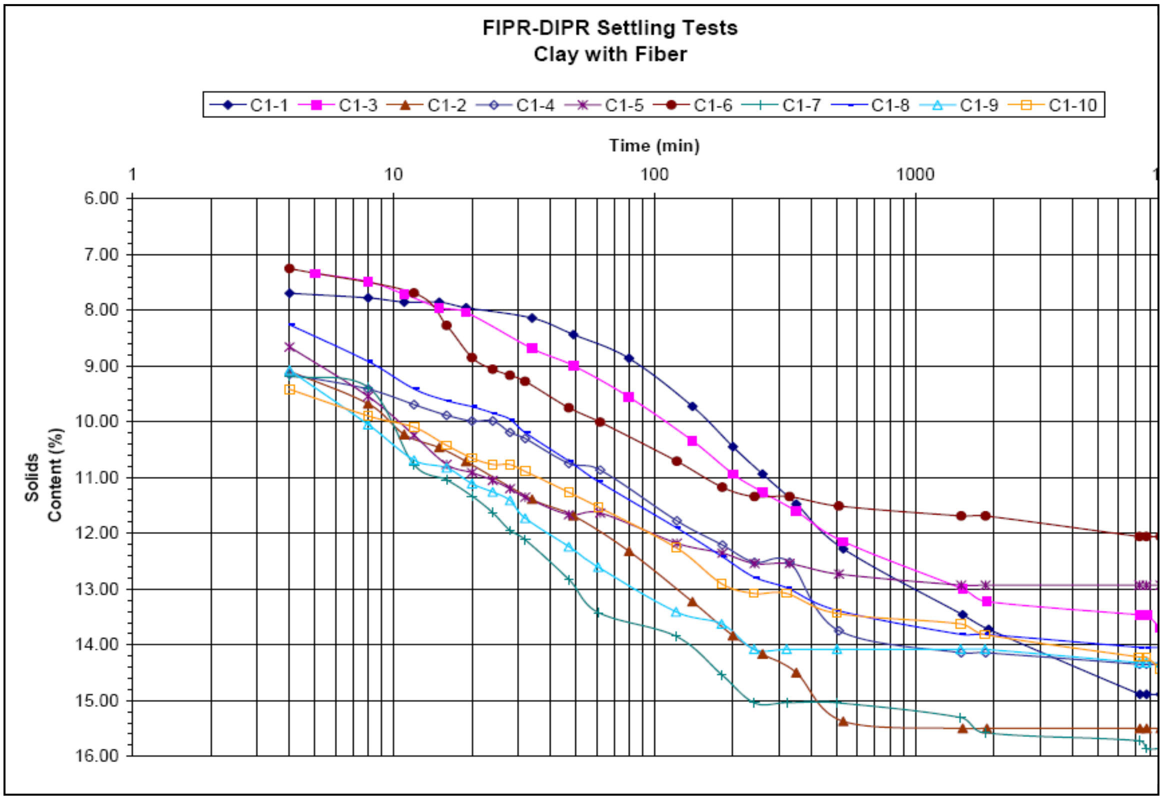


Figure 22. Laboratory Settling Test Results, Clay with Fiber.

Slurry Consolidation Tests

Slurry consolidation testing consisted of placing samples taken during filling of the three pipe columns into a test apparatus termed a constant rate of strain consolidometer (CRSC). The apparatus consists of a stainless steel cylinder 2.5 inches in diameter by 7.0 inches high. The base of the device contains a porous stone for water to escape from the sample, and a transducer for measuring pore water pressure. A loading piston with a load measuring transducer fits on top of the sample, and is connected to a load frame. Variable speed motors drive the load frame, and a displacement transducer measures the compression of the sample. The rate of loading is varied to maintain the excess pore pressure at a constant ratio to the applied load. In this manner, the test can be completed in a reasonable short period of time, on the order of a week or less.

The outputs from the pressure, load, and displacement transducers are fed directly into a dedicated computer, and the readings are used in a feedback loop to control the variable speed motor that drives the load frame. Data collection is continuous throughout the test, and provides tabulated values of void ratio vs. vertical effective stress, and consolidation ratio, c_v.

After the desired maximum effective stress is achieved, the sample is unloaded and removed from the test apparatus, and final moisture (solids) content determined.

Sample preparation for the CRSC testing consisted of allowing the samples to settle in five-gallon containers, then decanting off the supernatant water. For the Column 1 sample, the settled clay + pulp was placed directly into the test apparatus, at a clay solids content of 24%. However, when a light loading was placed onto the sample, the amount of consolidation (settlement) was too great for the apparatus to maintain a constant load. As a result, the early test readings showed considerable scatter, and the test took much longer to run that had been anticipated. The test results are shown in Figure 23 as void ratio (volume of voids/volume of solids) versus vertical effective stress. Once the loading reached about 80 lbs/sq. ft., the machine was able to increase the load monotonically, and the test was completed satisfactorily. At two stages of the test, the sample was allowed to remain under a constant load for a period of 72 hours. The resulting consolidation, or creep, was considerable, as can be seen in Figure 23 at the vertical stress values of 130 psf and 1000 psf.

For the subsequent tests on Columns 2 and 3 samples, the material was prethickened prior to placing into the CRSC apparatus. The prethickening was achieved in a constant load consolidometer, whereby small incremental dead loads were placed on a loading piston, and the sample allowed to consolidate before a higher load was placed. This process was continued until the effective stress reached approximately 50 lbs/sq. ft., at which time the sample was transferred to the CRSC apparatus. The results of the consolidation tests on Columns 2 and 3 materials are shown in Figure 23 as void ratio vs. vertical effective stress. Because of the sand addition to samples 2 and 3, the void ratio is significantly less than for Sample 1.

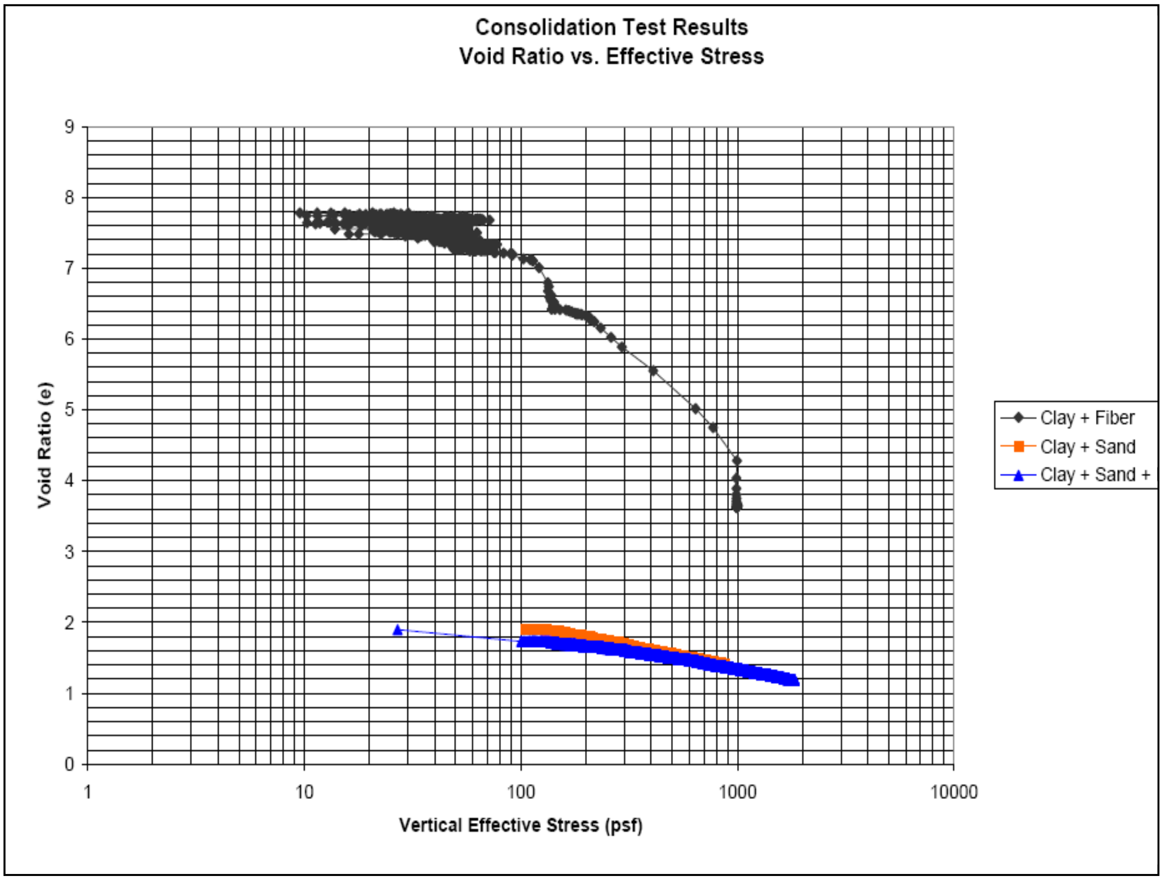


Figure 23. Consolidation Test Results Showing Void Ratio vs. Effective Stress.

The results of the CRSC tests on the three samples are shown in Figure 24 in terms of total solids content vs. effective stress, and in Figure 25 in terms of clay solids content vs. effective stress.

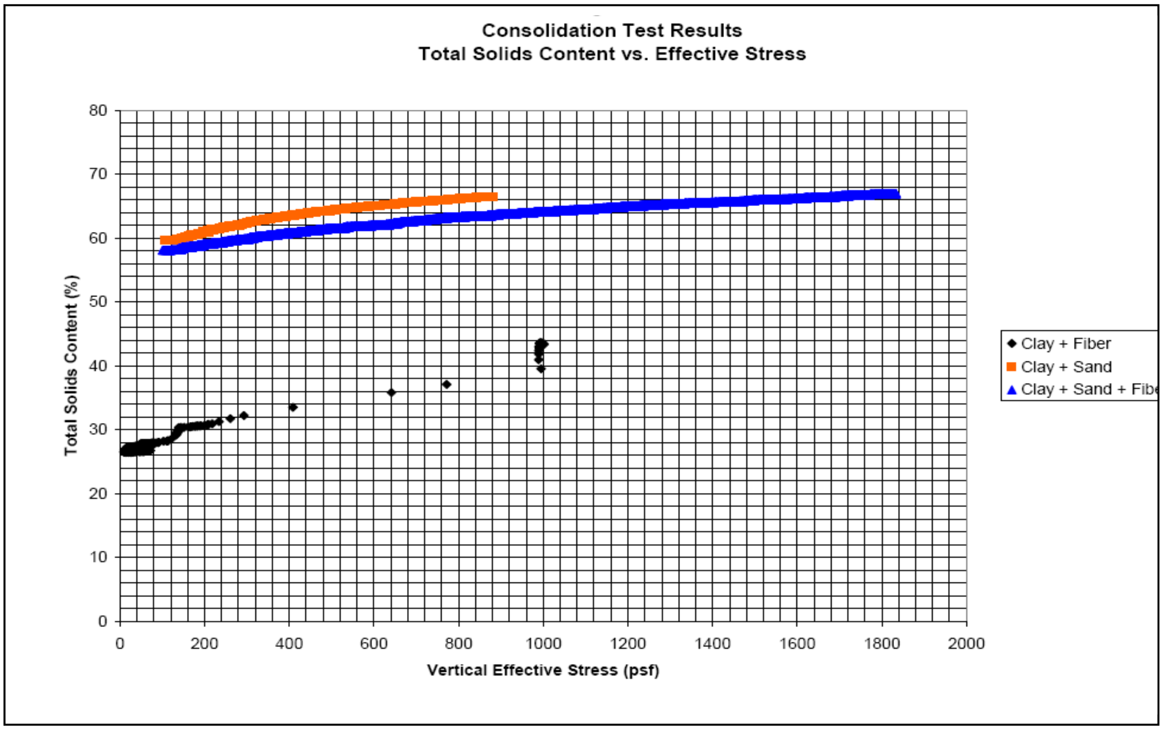


Figure 24. Consolidation Test Results Showing Total Solids Content vs. Effective Stress.

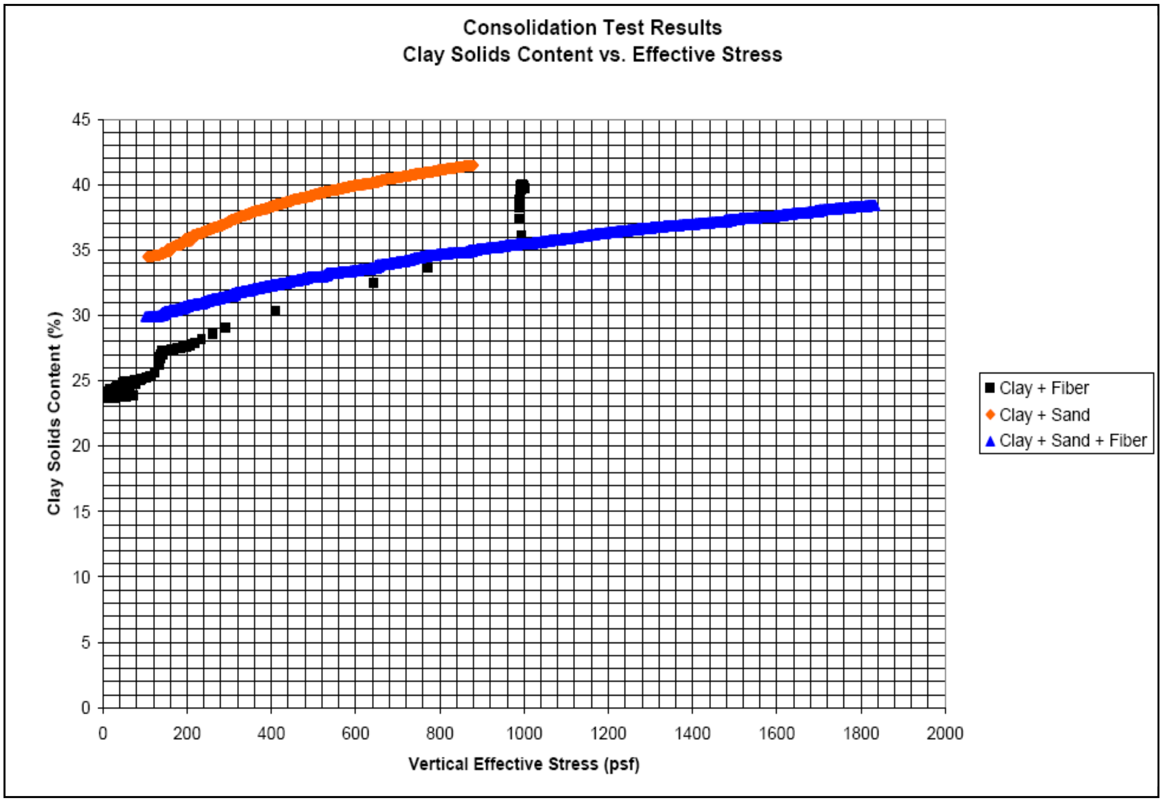


Figure 25. Consolidation Test Results Showing Clay Solids Content vs. Effective Stress.

Permeability Test Results

The coefficient of permeability, which expresses the rate at which fluid (water) can move through a porous material, was measured directly at high void ratios, using the prethickening equipment described above, for samples of clay + sand, and clay + sand + pulp. Also, during the CRSC testing, the permeability was calculated using the formula

$$k = c_v \gamma a_v/(1 + e_o) \qquad \text{(Equation 1)}$$

where

k = coefficient of permeability
c_v = coefficient of consolidation
γ = unit weight of water
a_v = coefficient of compressibility
e_o = initial void ratio

and the values of c_v, a_v, and e_o needed to calculate k are obtained from the consolidation test.

The results of the permeability measurements and calculations are shown in Figures 26 and 27. At low effective stresses (and low solids contents) the permeability values are in the range of .5 to 0.1 ft/day (1.8 × E-4 to 3.5 × E-5 cm/sec), which is typical of a silty sand to silt material. At higher solids contents, permeability values decrease markedly to .01 to .002 ft/day (3.5 × E-6 to 7.1 × E-7 cm/sec), which is typical of low to medium plasticity clay soils. These low permeability values are shown in Figure 26, which incorporates the same data as Figure 27 at an expanded scale.

Flocculation of the clays appears to result in higher permeabilities, hence more rapid outflow of water under load, than for non-flocculated clays. However, as the flocculated material consolidates to higher solids contents, the permeability becomes similar to unflocculated clay.

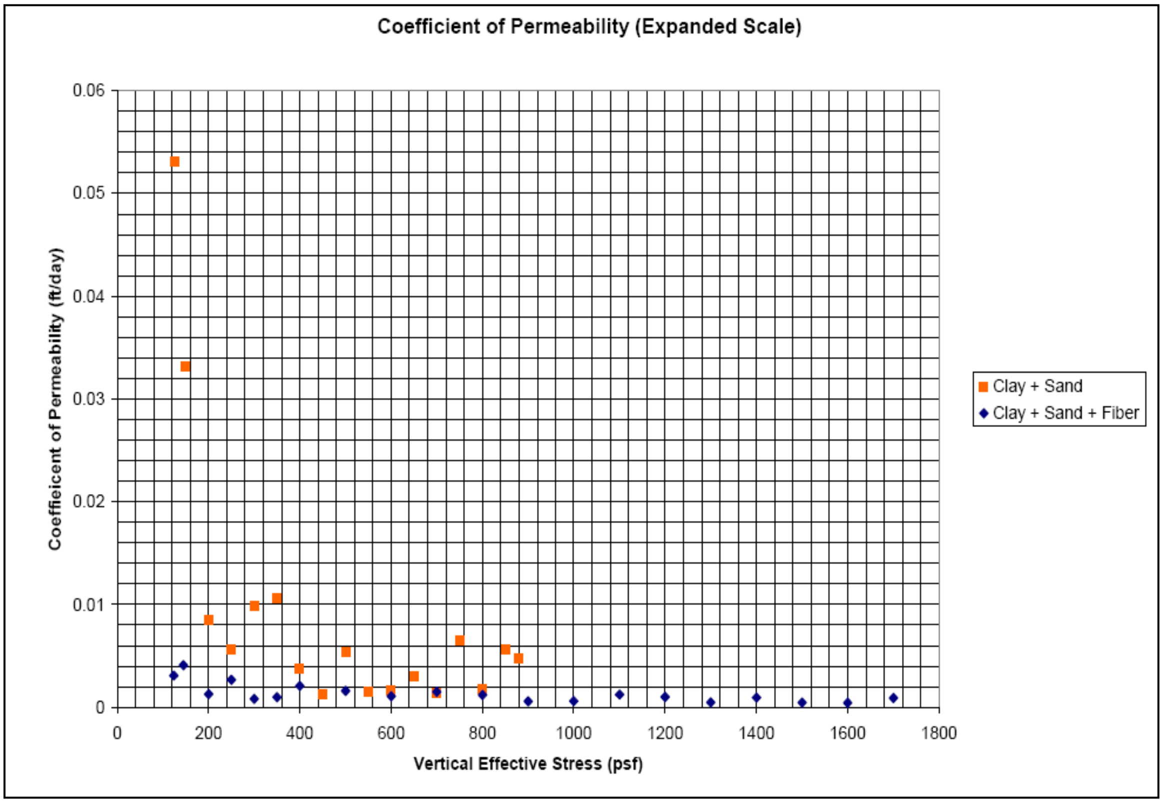


Figure 26. Coefficient of Permeability (Expanded Scale).

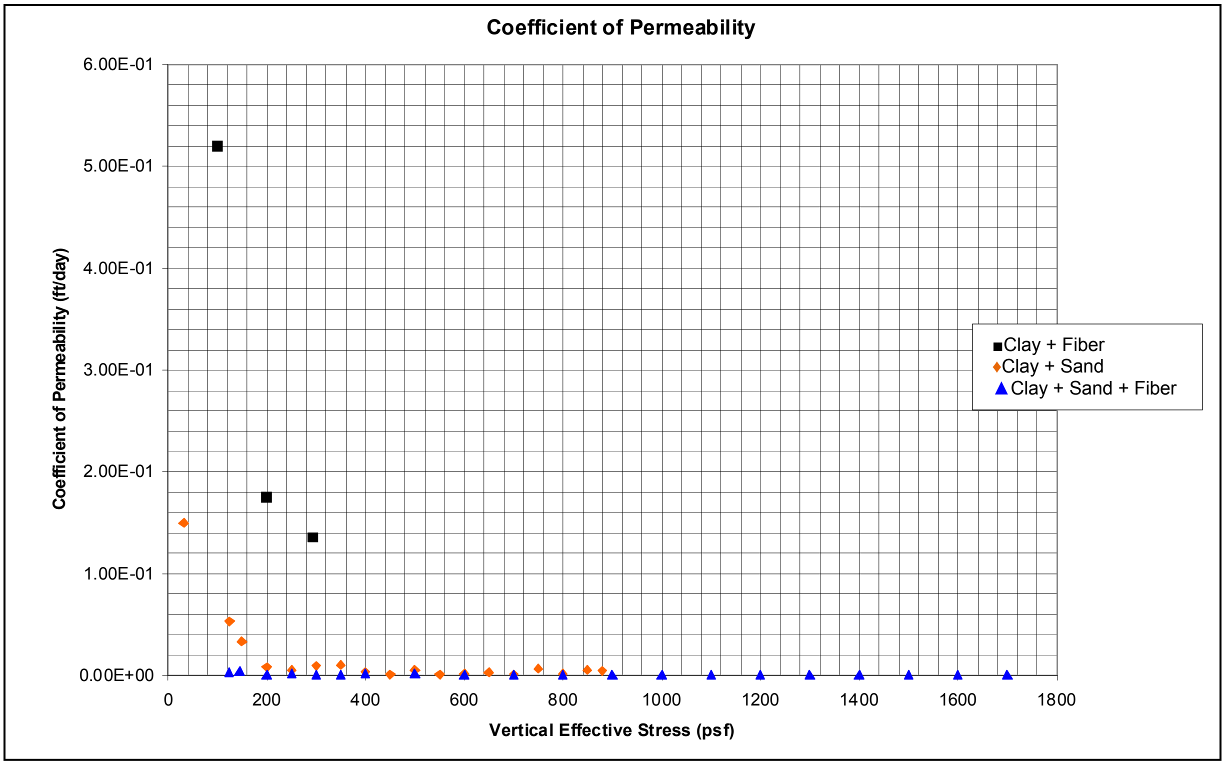


Figure 27. Coefficient of Permeability.

Direct Simple Shear Test Results

Shear strength measurements of the three mixes were made using a direct simple shear (DSS) test apparatus. The tests were run in accordance with ASTM D6528 (Standard Test Method for Consolidated Undrained Direct Simple Shear Testing of Cohesive Soils). The DSS test generates a fairly homogeneous state of shear stress throughout the specimen, and models field loading conditions more closely than other test systems such as triaxial tests.

The shear tests were run by transferring consolidated specimens from the CRSC test to the DSS apparatus, and consolidating them to vertical effective stresses ranging from 1500 lbs/sq. ft. to 6000 lbs/sq. ft. In this manner, both undrained shear strength as a function of effective stress, and effective stress friction angle, φ', and cohesion, c', can be determined.

The results of the DSS tests were used to estimate ultimate and allowable bearing capacity for both undrained and drained conditions, as a function of solids content. The undrained (φ= 0) case has a lower allowable bearing capacity, and is considered to be the more valid failure mode for a clay material.

DATA ANALYSIS AND EVALUATION

Self-Weight Consolidation

The column tests are representative of a vertical section of a large settling area or sand-clay mix area. By monitoring the height of the solids surface over time, and taking samples throughout the depth of the material at the end of the test, calculations can be made of the change in solids content and final solids content of the material. Comparisons can be made between actual height and solids content, and predicted height and solids content.

Predictions of height of fill and solids content versus time were made using SLURRY, a finite difference computer program developed for FIPR by Ardaman & Associates (1983). SLURRY predicts the consolidation behavior of phosphatic clays and clay/sand mixes under self-weight stresses and large strains for both filling and subsequent quiescent consolidation. Predictions of the solids contents versus time for the three column fills were based on correlations between consolidation properties and Atterberg Limits, developed by Carrier and others (1981, 1983); also see Carrier and Beckman (1984).

Subsequently, Wissa (1983a) conducted extensive research for FIPR (FIPR 02-073-097, "Evaluation of Phosphatic Clay Disposal and Reclamation Methods," 1983-1992), and extended the simplified empirical formulations based on test results obtained from constant rate of strain slurry consolidation tests on phosphatic clays sampled from various mine sites, as well as mixtures of sand and clay. The Carrier and Wissa relationships are based on statistical log-log linear correlations and least square regressions yielding best-fit curves of the data.

Void Ratio Versus Effective Stress Relationship

The relationship between void ratio and effective stress was developed by Carrier and coworkers (1981, 1983) and is given as follows:

$$e = \alpha \sigma'_{vc}{}^{\beta} \qquad \text{(Equation 2)}$$

Parameters α and β were developed to predict the compressibility relationship of phosphatic clays based on the plasticity index of the clay. These relationships were further defined by Wissa (1983b) as indicated below:

$$\alpha_c = 0.54 + 0.017(PI) \qquad \text{(in units of kg/cm}^2\text{)} \qquad \text{(Equation 3)}$$

$$\beta_c = -0.294 + (4.22 / PI) \qquad \text{(dimensionless)} \qquad \text{(Equation 4)}$$

Slight variations can be expected with regard to the magnitude of β, such that $\beta = -0.26 \pm 0.02$.

Void Ratio Versus Permeability Relationship

The relationship between void ratio, e, and the coefficient of permeability, k, was originally developed by Carrier and coworkers (1981, 1983). The relationship is as follows:

$$k=\gamma e^{\delta}. \qquad \text{(Equation 5)}$$

Estimates of the coefficients γ and δ were developed by Wissa (1983) based on correlations between the liquidity index and the coefficient of permeability. These correlations are based on least square regression analyses between log e and log k. Finally, values of γ and δ were plotted versus corresponding PIs, and the following empirical correlations with plasticity index were developed:

$$\gamma = (9PI)^{-3} \qquad \text{(in units of cm/sec)} \qquad \text{(Equation 6)}$$

$$\delta = 4.0 \pm 0.25 \qquad \text{(dimensionless)} \qquad \text{(Equation 7)}$$

A ζ-parameter was incorporated to introduce the variation commonly witnessed between field and laboratory permeability values. The in-situ, field permeability value is often greater than the laboratory permeability. The ζ-factor is calibrated based on a relative comparison of field performance with laboratory test data. Thus, the aforementioned formula for the γ-parameter respectively becomes:

$\gamma = \zeta\ (9*PI)^{-3}$, where ζ varies between 1 and 3. (dimensionless) (Equation 8)

Consolidation of Sand/Clay Mixes

The consolidation of sand/clay mixes was included in the original research by Bromwell & Carrier (1979) and was extended by the Ardaman FIPR research (1983). The consolidation behavior of a sand/clay mixture is highly dependent on the weight ratio of sand to clay. Typical ratios of 1:1 to 3:1 are used in practice. Wissa (1983) developed the compressibility and permeability relationships for sand/clay mixes based on modifications to the relationships given in Equations 2, 3 and 7 above. These modified formulations are given as follows:

$\alpha_t = \alpha_c / (1+(\rho_C/\rho_S)*SCR)$ (in units of kg/cm^2) (Equation 9)
$\beta_t = \beta_c * (1-0.04*SCR)$ (dimensionless) (Equation 10)
$\gamma_t = \gamma_c / (1+(\rho_C/\rho_S)*SCR)^{\delta}$ (in units of cm/sec) (Equation 11)

The formula for δ remains the same and is presented as follows:

$\delta = 4.0$ +/- 0.25 (dimensionless) (Equation 12)

SLURRY Input Parameters

Coefficients for α, β, γ, and δ are input directly to the SLURRY program, representing relationships of compressibility (i.e., void ratio versus effective stress) and permeability (i.e., permeability versus effective stress) as given in Equations 1 and 4. These coefficients are respectively designated as A, B, E and F.

SLURRY input also includes several index properties of the phosphatic clay or sand / clay mixture. These include the following: 30-day settled solids content; specific gravity of the solids; and initial water content or void ratio. Other applicable input parameters include: slurry inflow rate, filling time, changes in water table (if applicable), surcharge loading if any, and whether or not the system is single or double drained.

Values for the consolidation parameters were derived from both Atterberg limits tests on composite samples of the clay before mixing, and from the CRSC consolidation test results on samples from each column fill. The values used in the analyses are shown in Table 18.

Table 18. Consolidation Parameters for SLURRY Analyses.

Column	Initial		Specific Gravity	Clay Pl	Sand/Clay Ratio	Drainage	Consolidation Parameters Based on Plasticity Index				Consolidation Parameters Based on CRS Testing			
	Solids (%)	Moisture (%)					A kg/cm^2	B	E cm/sec	F	A kg/cm^2	B	E cm/sec	F
1	8	1150	2.4	64	0	Single	1.63	-0.228	1.39E-08	4.25	4.06	-0.188	1.00E-08	4.26
2	31.5	218	2.7	125	1.8	Single	0.95	-0.242	1.95E-07	4.25	1.15	-0.17	2.00E-07	4.25
3	18	456	2.4	82	2	Double	0.64	-0.223	5.30E-07	4.25	1.18	-0.168	1.06E-07	3.98

Comparison of Predicted Versus Measured Consolidation

Using the computer program SLURRY, the consolidation parameters from the slurry consolidation (CRSC) tests were used to predict the height versus time for the three column tests. The actual rate of fill used in the field for each column, and the maximum fill height, were modeled for each column. Then the quiescent settling/consolidation period was modeled, and compared to the measured heights versus time.

Figures 28-30 show the results of the modeling. The predicted height versus time relationship based on the Atterberg Limits (PI) is also shown on the figures.

Figure 28 shows the results for the clay/fiber mixture in Column 1. The measured height of the mix was 5.8 feet after 120 days. The predicted height based on the CRS data was 9.2 feet, and 6.4 feet based on PI. Thus, the PI correlation produced a much better prediction of the rate and amount of settlement than did the CRS test. Given that the CRS test was run on a composite of all of the clay/fiber mix placed in the pipe column, the reason for the poor prediction by the CRS test is not known at this time. Furthermore, as was pointed out in the "Laboratory Testing" section, and shown in Figure 23, the CRS sample was allowed to undergo secondary consolidation at two points during the test, which increased the final solids content by approximately 7%. Had this not occurred, the predicted height for the pipe column test would be even higher, which would make the prediction even further from the measured value.

Figure 29 shows the modeling results compared to the measured heights for the clay/sand mix in Column 2. The agreement between the predicted heights is remarkably good. However, both the PI and the CRS prediction methods underestimated the consolidation significantly. The measured height after 120 days was 10.3 feet, and the predicted height was 12.7 feet. At 20 days, the difference is even greater, with a measured height of 13.7 feet and a predicted height of 20.4 feet. This indicates that the clay/sand mix consolidated much faster than predicted. After 20 days, Column 2 was 77% consolidated, but the predicted consolidation at that time was only 31%. The significant increase in rate and amount of consolidation of flocculated clay/sand mix could provide a major benefit in terms of reducing storage volume requirements for a mine.

Figure 30 shows the modeling results compared to the measured heights for the clay/sand/fiber mix in Column 3. This mix also consolidated faster than either of the predictions, although the PI correlation is reasonably close after a period of approximately two months. The unfortunate leak and resulting loss of some mix from this column, described in the Column Filling section of this report, makes it impossible to interpret the height changes for this test. In addition to the loss of material, the leak resulted in double drainage from both top and bottom boundaries as well as a seepage gradient across the sample. Final sampling of Column 3 was done on March 29, 2007. However, the predictions were not extended past February 5, 2007, due to seepage of water and loss of material from the bottom of the pipe.

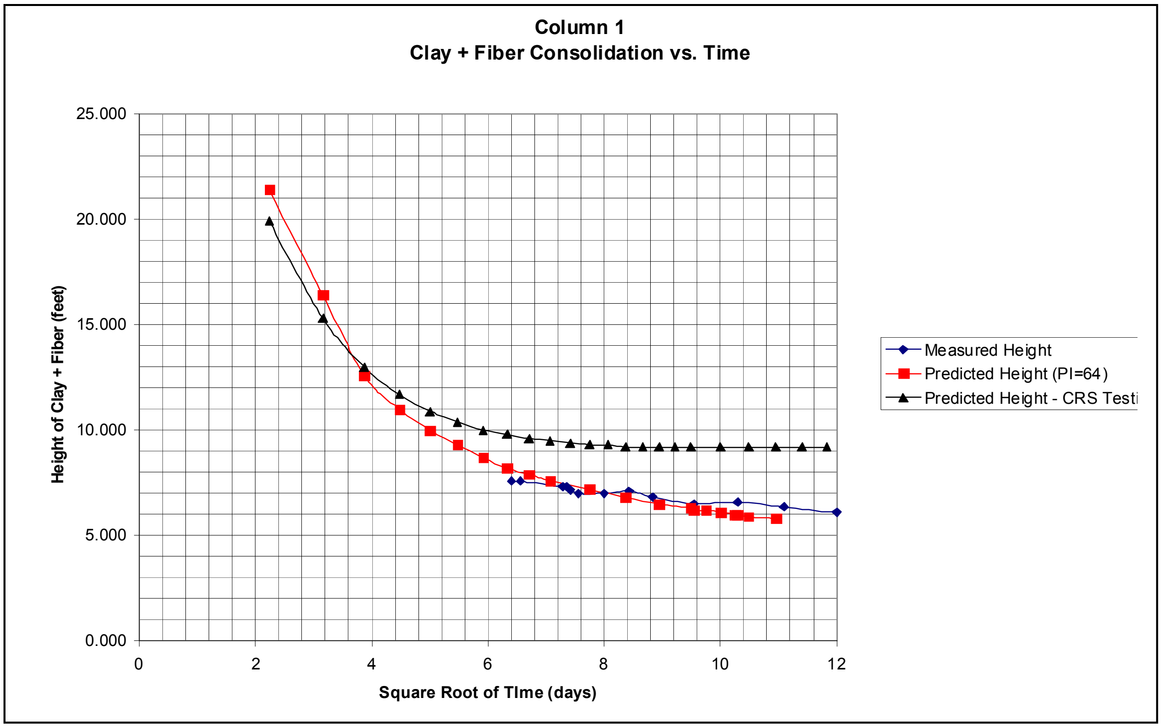


Figure 28. Clay/Fiber Consolidation vs. Time (Column 1).

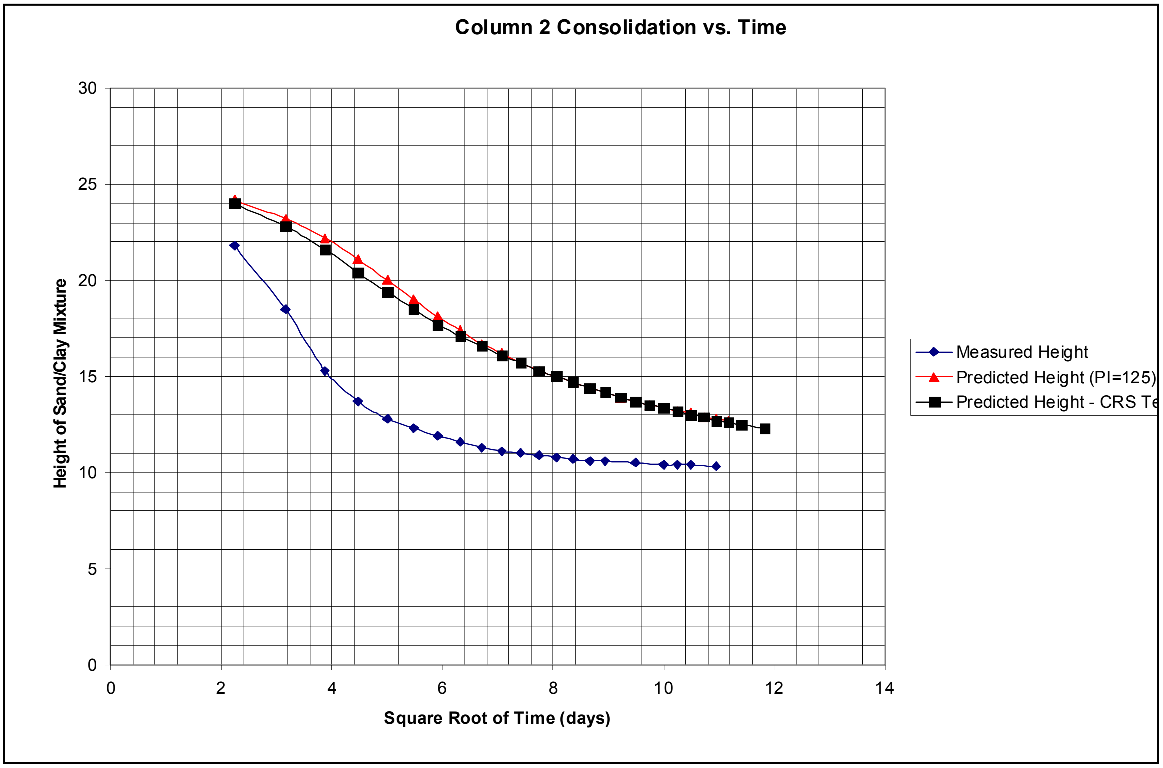


Figure 29. Sand/Clay Consolidation vs. Time (Column 2).

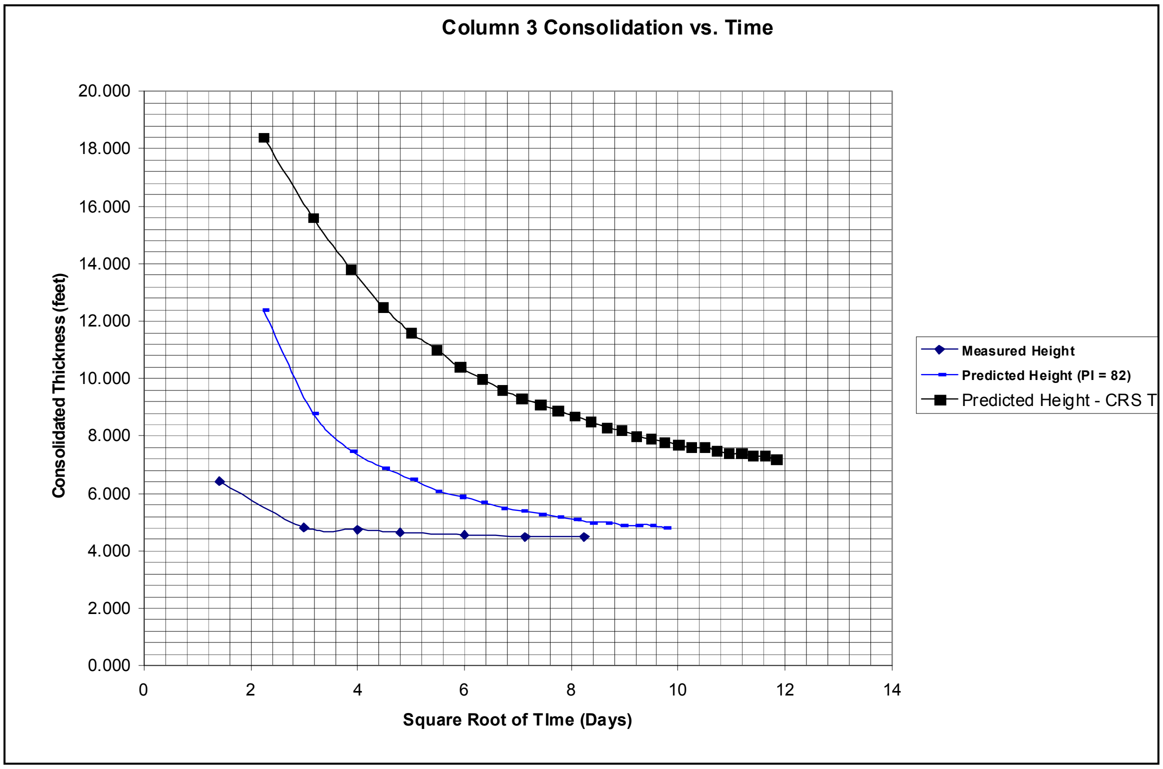


Figure 30. Clay/Sand/Fiber Consolidation vs. Time (Column 3).

Comparison of Final Solids Contents

As described in the "Field Activities" section, samples were taken from each pipe column at the end of the test. Although the details of each pipe column varied, in terms of height of fill and time of consolidation, several conclusions can be made from the results of the final solids contents and gradation measurements. The results are summarized in Table 19.

Table 19. Comparison of Pipe Column Tests.

Column	Initial						Final			
	Clay PI	Height (Ft.)	Total Solids (%)	Clay Solids (%)	% Minus 140 Sieve	Sand/Clay Ratio	Height (Ft.)	Total Solids (%)	Clay Solids (%)	% Minus 140 Sieve
1 Clay/Fiber	64	24	8	7.3	95.7	0	6.2	22	20.3	96.3
2 Clay/Sand	125	25	31.5	13.9	35.2	1.8	11.2	43.3	21.9	36.8
3 Clay/Sand/Fiber	82	18	18	6.7	33.1	2	2.4	32.5	28.7	83.7

The test results indicate that all of the clay mixes achieved a relatively high clay solids content, ranging from 20.3% for the clay/fiber mix to 28.7% for the clay/sand/fiber mix, in a relatively short time of approximately four months. Comparing the test results is complicated by several factors, including the relatively wide range of clay properties

(PI values ranging from 64 for clay/fiber to 125 for clay/sand), the relatively low solids contents for placement of the mixes into the columns (which led to separation of sand and clay in both Columns 2 and 3, and the leakage from the bottom of Column 3 during the test. However, general conclusions can be made as follows:

The total solids content after consolidation was significantly higher in Column 2 (clay/sand mix). This column also had the highest plasticity clay, which would imply the worst consolidation characteristics.

The highest clay solids were obtained in Column 3 (clay/sand/fiber). However, this column had leakage out of the bottom of the column, as well as induced seepage forces, which likely contributed to consolidation of the clay. Also, most of the sand apparently migrated to the bottom of the column, and ultimately leaked out, resulting in a reduction of sand/clay ratio from 2.0 at filling, to 0.2 at end of test. In addition, the PI of the clay was relatively low (92), so the fact that final solids content of the clay was higher than the clay/sand Column 2 cannot be attributed to the addition of fiber to the Column 3 mix.

The consolidation results, although to a large extent masked by operational variations between the three tests, do not indicate that addition of fiber to clay, as compared to adding sand to clay, is effective in subsequent settling and consolidation behavior.

The major improvements to settling and consolidation of the clays in this test program can be attributed to (1) effective flocculation of the clay, which accelerated both the settling and consolidation in the pipe columns, and (2) the admixing of tailings sand, which significantly increased the unit weight and hence the self-weight stresses causing consolidation of the clay/sand mix.

Shear Strength and Bearing Capacity

The results of the Direct Simple Shear (DSS) tests were used to estimate ultimate and allowable bearing capacity as a function of solids content. An undrained ($\varphi = 0$) failure condition has a lower allowable bearing capacity, and is considered to be the more valid failure mode for a clay material.

The calculated ultimate and allowable bearing capacities are shown in Table 20. The allowable bearing capacity values range from approximately 900 to 3000 psf for undrained failure. The values generally increase with higher solids contents, and with sand addition, although the scatter in the data does not support a good correlation.

Table 20. Shear Strength and Bearing Capacity.

Column No.	Test ID	Ultimate Shear Strength (psf)	Moisture Content (%)	Percent Total Solids	Undrained Ultimate Bearing Capacity (psf)	Undrained Allowable Bearing Capacity (psf)
1	DS-1	1075	74.3	57.4	5375	1792
1	DS-2	1800	67.1	59.8	9000	3000
1	DS-3	1095	86.4	53.6	5475	1825
1	DS-4	1695	69.1	59.2	8475	2825
2	DS-5	2074	43.2	69.8	10370	3457
2	DS-6	3729	35.0	74.1	18645	6215
3	DS-7	1952	30.1	76.9	9760	3253
3	DS-8	3333	27.5	78.4	16665	5555

It should be noted that these bearing values are for very high solids contents, which represents material that is either consolidated under a high load (surcharge), or desiccated due to evaporation. It should also be noted that desiccation generally only extends a few feet into a deposit of phosphatic clay, and hence would support only a small foundation.

In general, the ultimate bearing capacity (q_u) of a phosphatic clay or clay mix can be expressed as

$$q_u = 5S_u, \qquad \text{(Equation 13)}$$

where S_u = Undrained Shear Strength at specified solids content

The shear strength to be used in the analysis is the average strength over a depth that increases as the size of the loaded area increases. A detailed evaluation of bearing capacity for various sized loads on various combinations of clay mix, consolidated under various loads, is beyond the scope of this report. However, in general terms, it may be concluded that for the same consolidation conditions and the same applied loading conditions, the bearing capacity of a 2:1 sand/clay mix is substantially higher than a clay/fiber mix. However, the allowable bearing capacity of any phosphatic clay mixture that is consolidated under self-weight alone, even after some drying and desiccation, will be on the order of a few hundred pounds per square foot or less, which is far too low for practical construction purposes. In order to achieve practical values of allowable bearing capacity, either a high solids content (generally 50% or higher total solids), or increased strength by chemical stabilization (e.g., lime or Portland cement soil mixing techniques) will be required.

ECONOMIC ANALYSIS

The economics for the FIPR/DIPR (UF Process) for thickening phosphatic clay have been revised to include the Deep Cone Thickener. Included below are: Basis for Estimate; a comparison and initial costs of clay mass transport systems (Table 21); the preliminary DCT clay estimate (Table 22); and the proposed UF Clay Process Flow Diagram (PFD) (Figure 21).

The Basis for Estimate shows the 5MM TPY mine basis with 28% clay and 28% product in the ore. Under the current practice using disposal of flocculated clays, about ten clay ponds are required for a 25-year mine life versus only two for the revised UF process.

Table 21 shows three options for the 40% clay paste transport compared to a conventional clay transport (pumping) system. Both the diaphragm pumps and the Rail-Veyor® are surprisingly competitive. Even the belt at 45% solids is much cheaper than the current centrifugal pumps at 3% solids. The HDPE pipe costs are large. We chose to use a mid-range $12,000,000 for the mass transport.

The higher prices should surprise no one, since we are 3.5 years into the largest commodity equipment price increase in 30 years. This is prone to give sticker shock to many who have not done frequent estimates during this time of change. For instance, many of the existing mines would cost $250-400 MM if built today for plant facilities only. The cost of a densification system at 10-15% of these prices is a reasonable fact.

Table 22 is a preliminary cost estimate with the entire densification system included. This includes the cyclones, the DCT system, the mass transport system, the floc system and the electrical MCC and transformer. For this estimate, the system is fed from the feed pond with pumps similar to, but with less power than, the current clay pumping system.

Finally, the two floc systems were estimated as though they were the current soda ash systems used at several mines now but with downsizing.

In this estimate, of all the plant sand is used and the predicted production of 45% solids for the sand clay mixture. This means only the plant GMT tails pump will be needed with a short length of pipe instead of much longer pumping lines. **With 25% contingency, the final estimated figure is $40,038,099 for this revised process.**

Using the Net Present Value method with Table 21 parameters, the following was calculated to compare current practice to the revised process for a 25-year mine:

NPV/Cost of 8 clay ponds, $25MM ea, 3 yrs apart	$74,874,997
NPV/Cost of clay pipe maintenance	6,880,666
NPV/Cost savings for less tails equipment	2,099,765
NPV/Cost savings for less tails maintenance	952,976
NPV/Cost of Densification System	(40,038,099)
NPV/Cost of Densification maintenance	(2,001,905)

NPV/Savings of $1.50-1.20/ton clay, 25 yrs	13,615,500
Reclaimed land price improvement	4,393,399
Total	**$60,777,299**

Using the Annual Cost method with Table I parameters, the following was calculated:

Annual cost of 7 ponds/main, 3years apart, 25 years	$8,715,000
Annual cost of pipe maintenance	758,033
Annual cost savings eliminated tails equipment	245,874
Annual cost savings of maintenance on tails	104,988
Annual cost of Densification equipment, 25 years	(4,410,997)
Annual cost of Densification maintenance	(220,550)
Annual reagent cost for 7MM TPY clay	1,500,000
Reclaimed land price improvement	423,518
Total	**$7,115,866**
Net savings per ton of phosphate, 5MM TPY	**$1.42**

With real prices for Florida rock perhaps as high as $60-80 per ton (if it was available) and imported rock soaring to $250 per ton, this cost may not be unreasonable. It is also possible, cost reductions may occur from further process development, particularly in the densification system itself.

The conclusion is that further process development is needed, including a full-size 24" cyclone test. A cost estimate should be conducted then using 1:1 SCR as proposed in the flow diagram (Figure 31). In addition, the number of deep cone thickeners should be recalculated based on lab testing of the cyclone underflow, which was not done in the present estimates. The larger full-scale test of system components might cost $10,000,000 and would have to be funded by the industry.

Basis for Preliminary UF DCT Estimate

A. Per FIPR (P. Zhang), a product-to-clay ratio of 1:1 is used. Phosphate mine production is 5 MM TPY from matrix ore with 28% product, 28% clay and 44% reclamation material (sand, phosphate and oversize). At 90% operating factor, this produces about 634 dry short TPH of clay. The solids are mixed 39% clay and 56%

sand. The final base flow is 1441 dry TPH at 9222 GPM and 45% solids. Further estimates need to be done using 1:1 SCR.

B. With 3-6% oversize, virtual all of the sand tails are used in densification. Sand would be stored in a pile over the feed tunnel to densification. This will apparently eliminate most of the flotation tails system except for the GMT and a short pipe to the storage pile.

C. The current tails system is taken as three miles long with three lift pumps using 20” SDR17 HDPE pipe. Only the initial GMT pump and a short 0.5 mile length of pipe will be required for the revised process.

D. Clay feed to the feed pond is 3% solids. It exits at 5% solids. Densification produces 45% solids minimum with 40-50% possible. Comparison to currently used flocculated clay disposal costs is the goal.

E. Clay tanks for 3% solids are common to the current flow sheet as well as the densification revision. Their cost is not included for the densification system.

F. Tank overflows to nearby clay ponds are common to current and revised flow sheets. There will be two initial clay ponds near the plant for both cases.

G. This process will recycle flocculants by using the geometry of the feed pond and internal recycle. The densification system water removal is far from the plant and near the clarified water inlet. The rest of the plant will have a more remote removal to allow biodegradation of the flocculants, avoiding undesirable recycle to flotation.

H. The Eimco 30-meter Deep Cone Thickeners were used because they are the only ones currently in service. Savings here is possible with larger thickeners not yet in service.

I. The euro was valued at 1.55 to the US dollar for conversion of the Geho diaphragm pump quote. 10% interest rate is used for the value of money in the economic analysis. Standard interest factor tables were also used.

J. $25MM builds a clay pond that will hold 25MM tons of clay. Ten clay ponds will be required for a 25-year mine at 5MM TPY clay for the 5MM TPY mine. Only the two initial ponds will be required for the revised flow sheet. The eight additional ponds will be built every three years with the current process for an average $8.3MM capital per year.

K. The two initial clay ponds will be the feed storage ponds for this revised process.

L. A half-mile by half-mile clear water pond near the plant is assumed. The pond cost is not used because a current typical mine usually has a pond or ditch equivalent at a similar cost. The clear pond is required to age and slightly biodegrade any residual flocculant for flotation avoidance.

M. The revised process clarified water from reclamation is returned to the plant via gravity ditches and pumps similar to current tails operation. The cost differential is neglected for now, but the water return is significantly less.

N. The sand/clay paste viscosity is similar to wet mixed concrete, with the 45% solids having a very low angle of repose, as seen in the UF and UK studies.

O. Electrical transformers in the field and a Plant Motor Control Center (MCC) are included. Primary electrical service of 25,000 volts is not included because normally it would be installed during mining of the reclamation area.

P. The floc cost is predicted to be $1.20 per ton of clay by UF for the revised process. This is used in the economics versus current $1.50 or higher.

Q. Land value reclaimed by the densification process is worth about $6,000 more per acre than land in a conventionally reclaimed clay pond for agriculture.

R. The current plant flocculation practice was estimated using $1.50 floc per ton per FIPR (P. Zhang).

S. No alternatives to Eimco DCTs are considered. Some are recently available.

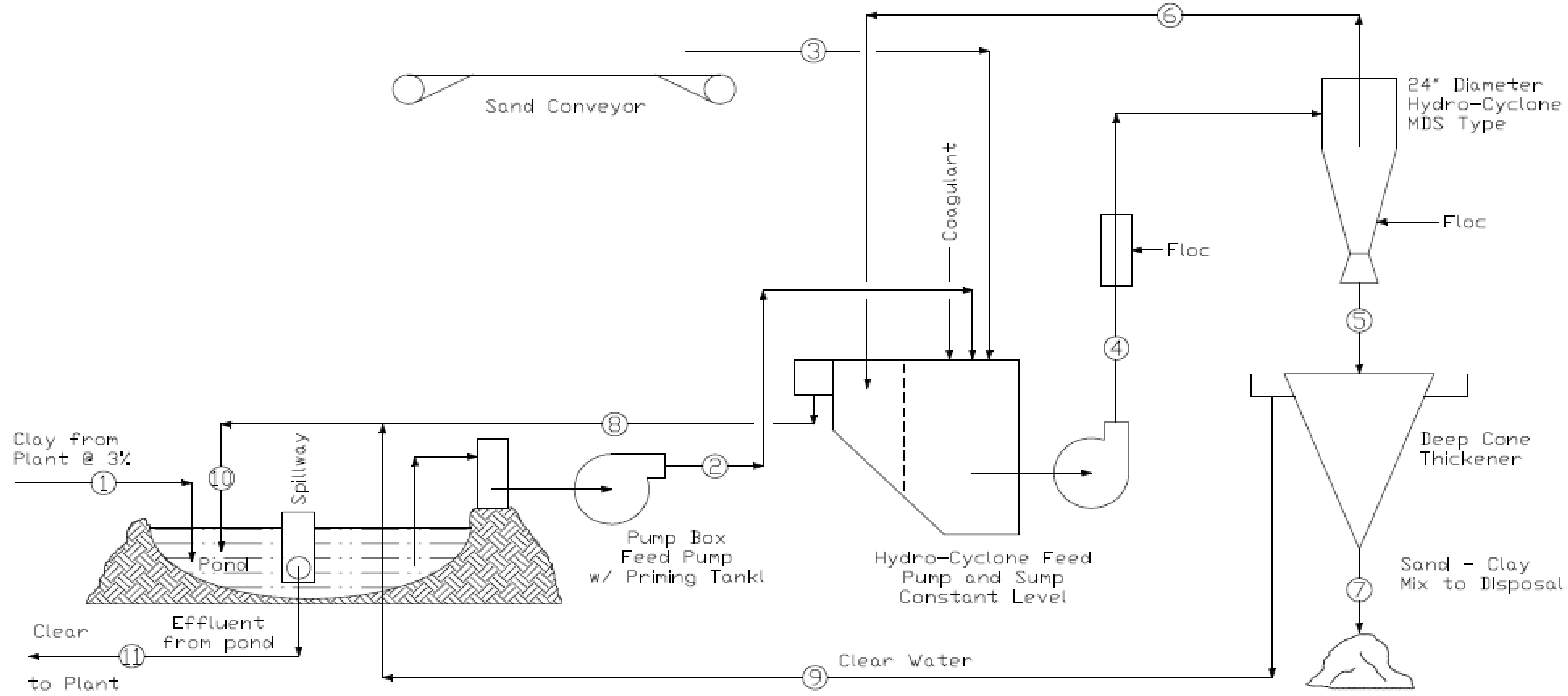
T. No fly ash was considered for its lack of positives in the SFM study.

Table 21. Cost Comparison of Mass Transport Systems.

Item	Belt	Diaphragm Pumps	Rail-Veyor$^{®}$	Current Centrifugal Pumps
% Solids	45	45	45	3
TPH	1,441	1,441	1,441	634
GPM	9,221	9,221	9,221	82,959
Distance	3 miles	3 miles	3 miles	9 miles
Pipe Type	None	18” Sch 80 AR	None	48” SDR17 HDPE
No Pumps	None	2	None	3
HP	2,000	3,000	3,000	4,500
Miscellaneous	750 fpm 72" belt Krupp	Geho Triplex Piston VFDs	6 trains 1328' ea	GIW or Thomas, VFDs
Pri Cost	$15,725,000	$6,510,000	$10,000,000	$4,500,000
Pipe Cost	0	$2,333,755	0	$10,408,662
Pipe Installation	0	$2,333,755	0	$4,752,000
Field Elec.	$500,000	0	$550,000	0
Feed System	$100,000	$500,000	$100,000	$600,000
Rail Installation	0	0	$200,000	0
Miscellaneous			$1,200,000 field civil	
Total	**$16,325,000**	**$11,677,510**	**$12,050,000**	**$20,260,662**

Table 22. Engineering Estimate Guide for Detailed Cost Estimates for FIPR/DIPR Process.

PENN PRO, INC.				Detailed Estimate				39571
Engineering Estimating Guide				Title: Table III. Preliminary UF DCT Clay Estimate				: JTE
Client: PENN PRO				Job No. 132-0701				
Quantity			Description	Unit Costs		Material Costs	Labor Costs	Total
Item #	Material	Labor (Hr.)		Materials	Labor (Hr.)			
1	3	--	DCT vessels (30 meters by 40' high), agitators and controls, elevated	3,000,000	--	9,000,000	0	9,000,000
1A	83	--	Concrete DCT, yards	1,000		83,000	0	83,000
1B	3	--	Misc. solids chutes	25,000	--	75,000	0	75,000
1C	6,000	--	Clarified water pipes to pond, 48" SDR17	151	--	906,000	0	906,000
1D	3	--	Mass flow for clay (ea.)	30,000	--	90,000	0	90,000
2	1	--	Tunnel for sand addition with 3 automatic gates	325,000	--	325,000	0	325,000
2A	600	1,275	Conveyor belt, supports, idlers, etc. for sand transport (ft.)	150	70	90,000	89,250	179,250
2C	3	--	Weigh belts and associated controls for each DCT	45,000	--	135,000	0	135,000
2D	442	--	Concrete for tunnel, cy fd tk, pumps.	1,000	--	442,000	0	442,000
3	3	2,000	Clay feed pumps, pipe and controls	325,000	70	975,000	140,000	1,115,000
3A	1	--	Cyclone feed tank, 80D X 40H	1,131,008	--	1,131,008	0	1,131,008
3B	3	2,000	Cyclone feed pumps and pipe	569,000	70	1,707,000	140,000	1,847,000
3C	51	300	Cyclones, 24"	6,300	70	321,300	21,000	342,300
3D	200,000	--	Cyclone support steel (lbs. installed)	4	--	800,000	0	800,000
3E	17	--	Cyclone controls, installed	15,000	--	255,000	0	255,000
4	1	--	Mass transport system for 45% solids thickened paste (see Table II)	12,000,000	--	12,000,000	0	12,000,000
5	2	--	Floc silos, screw, metering, blower, filter bags, etc.	150,000	--	300,000	0	300,000
5A	3	--	Powder pumps	30,000	--	90,000	0	90,000
5B	4	--	Two agitated mix tanks and two agitated use tanks. FRP, 10,000 gals.	50,000	--	200,000	0	200,000
5C	6	--	Metering pumps	7,500	--	45,000	0	45,000
5D	2,250	--	Floc and water tubing installed (ft.)	20	--	45,000	0	45,000
5E	12	--	Control loops, floc	15,000	--	180,000	0	180,000
5F	1	--	Water pump	50,000	--	50,000	0	50,000
6	1	--	MCC building	175,000	--	175,000	0	175,000
6A	1	--	Transformer	100,000	--	100,000	0	100,000
6B	1	--	Switch gear	50,000	--	50,000	0	50,000
						29,570,308	390,250	29,960,558
				Sales Tax	0.07	2,069,922		2,069,922
				Contingency	0.25			8,007,620
							GRAND TOTAL	40,038,099



Flow Rates

Stream	1	2	3	4	5	6	7	8	9	10	11
Solids TPH	15	17.25	12	29.25	27	2.25	27	2.25	0	2.25	0
% Solids	3	5	85	8.8	16	1.5	45	1.5	0	0.8	0
Slurry, TPH	500	345	14.12	332.39	168.75	150	60	150	168.75	281.25	454.11

Figure 31. Suggested Process Flow Diagram for FIPR/DIPR Process.

CONCLUSIONS

Based on the data collected and the testing and analyses reported herein, the following general conclusions can be made:

1. Over 100,000 tons/year each of waste mixed paper, cardboard, and yard waste are available at Polk County at a cost of shipping and handling. The pulping costs are also found to be reasonable. However, after running the pilot plant, it became obvious that fiber addition might not be beneficial to consolidation of the produced sand/clay mixture.

2. Hydrocyclones can be used to dewater flocculated sand/clay mixture.

3. Use of anionic/ cationic polymer reagent scheme is important to the formation of strong flocs that can be dewatered and consolidated without sand segregation.

4. Statistical designs were used to run the pilot plant at different conditions of reagents/dosages and SCR. Three designs were used to test reagents from three different suppliers. A sand/clay mixture as high as 56% solids can be obtained depending on the sand/clay ratio. It is also interesting to note that regardless of the supplier, a combination of high molecular weight (15-26 M) anionic polymers and cationic polymers (1-5M) result in a strong composite of sand and clay mixture.

5. The plasticity index values (Atterberg Limits) for the composite clay samples for the column fills had PI values of 64, 125, and 82 for Columns 1, 2, and 3 respectively. Although this range is large, it indicates that the plasticity was generally in the lower range encountered for phosphatic clay.

6. The total solids content after consolidation was significantly higher in clay/sand mix than in clay/pulp mix. The clay/ sand mix also had the highest plasticity clay, which would imply the worst consolidation characteristics.

7. The consolidation results, although to a large extent masked by operational variations between the three tests, do not indicate that addition of fiber to clay, as compared to adding sand to clay, is effective in improving settling and consolidation behavior.

8. It may be concluded that for the same consolidation conditions and the same applied loading conditions, the bearing capacity of a 2:1 sand/clay mix is substantially higher than a clay/fiber mix. However, the allowable bearing capacity of any phosphatic clay mixture that is consolidated under self-weight alone, even after some drying and desiccation, is too low for practical construction purposes. In order to achieve practical values of allowable bearing capacity, either considerable surcharging, extensive desiccation, or chemical stabilization must be accomplished.

9. However, consolidation data indicate that a surcharge of only two feet of sand tailings or overburden, giving a vertical effective stress equivalent to 200 psf, will lead to an increase of total solids content to 60%, which could be of load-bearing capacity.

10. The major improvements to settling and consolidation of the clays in this test program can be attributed to (1) effective flocculation of the clay, which accelerated both the settling and consolidation in the pipe columns, and (2) the admixing of tailings sand, which significantly increased the unit weight and hence the self-weight stresses causing consolidation of the clay/sand mix.

11. A preliminary cost analysis conducted by Penn Pro suggested that FIPR/DIPR cost could range between $0.95 and $1.60/ ton of phosphatic clay.

12. Using the Net Present Value method a net savings $1.42 per ton of phosphate was calculated as compared to the current practice. It is also possible, cost reductions may occur from further process development particularly in the Densification System itself.

13. The conclusion is that further process development is needed, including a full-size 24”or larger cyclone test. A cost estimate should then be conducted using 1:1 SCR using a proposed flow diagram. In addition, number of deep cone thickeners should be recalculated based on lab testing of the cyclone underflow, which was not done in the present estimates.

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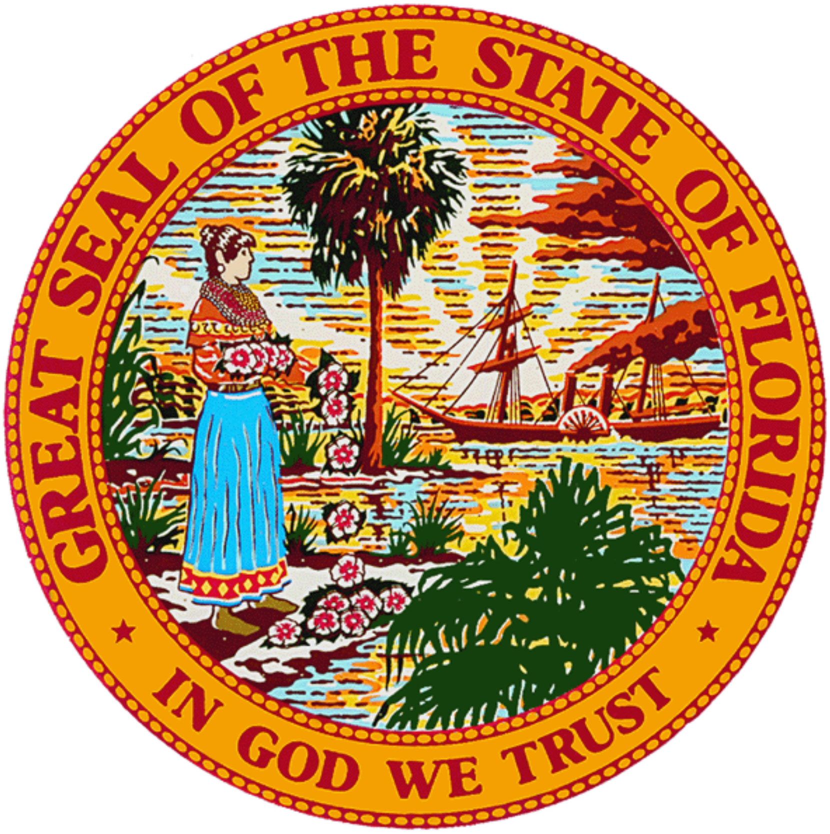
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