Publication No. 02-042-044

EVALUATION OF PHOSPHATIC CLAY DISPOSAL AND RECLAMATION METHODS

Volume 7: Engineering Properties of Flocculated Phosphatic Clays

Prepared by Ardaman & Associates, Inc.

under a grant sponsored by the

Florida Institute of Phosphate Research

Bartow, Florida

November, 1986

FLORIDA INSTITUTE OF PHOSPHATE RESEARCH

The Florida Institute of Phosphate Research was created in 1978 by the Florida Legislature (Chapter 378.101, Florida Statutes) and empowered to conduct research supportive to the responsible development of the state's phosphate resources. The Institute has targeted areas of research responsibility. These are: reclamation alternatives in mining and processing, including wetlands reclamation, phosphogypsum storage areas and phosphatic clay containment areas; methods for more efficient, economical and environmentally balanced phosphate recovery and processing; disposal and utilization of phosphatic clay; and environmental effects involving the health and welfare of the people, including those effects related to radiation and water consumption.

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EVALUATION OF PHOSPHATIC CLAY DISPOSAL AND RECLAMATION METHODS

Volume 7: Engineering Properties of Flocculated Phosphatic Clays

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Research Project FIPR 83-02-042
Final Report, December 1985

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PERSPECTIVE

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Large quantities of phosphatic clay are produced as a result of phosphate rock mining and beneficiation in Florida. Approximately 100,000 tons/day of phosphatic clay are generated by more than 20 active mines. The phosphatic clay is transported in slurry form, at an average solids content of 3 to 4 percent, for disposal in impoundment ponds or settling areas. The highly plastic phosphatic clays are characterized by a relatively slow rate of consolidation; the solids content reaches on average 9 percent after a few days of settling and increases only to about 18 percent after one year. Several years (about 10 years) are generally required to attain an average solids content of 25 percent.

The phosphate industry has been using the "conventional" procedure of clay disposal in settling areas for many years. Recently, this method of disposal has received extensive criticism. One of the more significant disadvantages of this disposal technique is the consumptive use of large quantities of water entrained in the pores of phosphatic clays, necessitating withdrawal of fresh make-up water from the Floridian Aquifer. It is estimated that at 20 percent solids and at the 40 million tons per year phosphate production rate in Florida, water entrained in the pores of the clay amount to about 50,000 gpm. Some of the water is recoverable with time. Increasing the percentage clay solids in settling areas from 20 percent to 30 percent reduces water losses from 50,000 to 20,000 gpm if all the water can be recovered. Increasing concern over water supplies, particularly in expanding population centers and in coastal areas, has led to extensive research to improve consolidation of the phosphatic clays and recover some of the water.

The risk of failure of an above ground active settling area is also a public concern. The probability of a dam failure during slurry impoundment is extremely small due to improved design and construction procedures and extensive monitoring required for compliance with the comprehensive rules of Florida's Department of Environmental Regulation. These revised rules have been in effect since 1971 (Chapter 17-9) and dams constructed in accordance with these regulations have an excellent safety record. However, dam failures were not uncommon in the forties, fifties and sixties, and the off-property spill of clay slurry to streams with associated reports of fish kills have not been forgotten by the public at large.

Another area of concern is associated with the reclamation of clay settling areas. Because of the low percent solids and slow rate of consolidation, large volumes are needed to store the waste clays and above ground storage is generally required. Reclamation of these areas is generally a slow process. This is conventionally accomplished by promoting the development of a desiccated crust to support a sand tailings cap, and occasionally, an overburden cover. Reclaimed clay areas are subsequently vegetated and used for cattle grazing, wildlife habitat and/or for recreational and agricultural purposes. The low shear strength of the settled clay and continued settlement as a result of clay consolidation are not desirable for supporting other land uses such as the development of housing projects. In addition, reclamation of the land to original grade seems to be generally favored by regulating agencies and it is not easily achievable with conventional disposal methods.

The problems associated with phosphatic clay disposal have stirred research efforts for improved dewatering and alternative disposal methods since the 1950's. Various phosphatic clay dewatering schemes have been proposed over the years. Many of these methods are not economically feasible, but others are considered potentially viable disposal methods.

Recognizing the problems associated with phosphatic clays, the Florida Institute of Phosphate Research has provided support for several projects that directly address the topic of phosphatic clays. Other projects containing problems of phosphatic clays as part of the scope of their investigation, are also supported by the Institute.

The Institute's research program addresses the phosphatic clays from several perspectives: exchange of knowledge about phosphatic clays, reduction of water loss to the clays, stabilization of clays, evaluation of conventional and developing techniques of clay disposal and reclamation methods, recovery of phosphate values lost with the clays, and utilization of phosphatic clays for different purposes.

From the perspective of exchange of knowledge and information about phosphatic clays, the Institute granted Central Florida Regional Planning Council a project (FIPR #81-02-020) to organize a seminar concerning a policy officials guide to phosphate waste clay reclamation. Another project (FIPR #84-02-052) was granted to the Engineering Foundation to organize a conference regarding flocculation, sedimentation, and consolidation of phosphatic clays. On the same line, University of Florida was granted a project (FIPR #86-02-058) to conduct a symposium on waste clays.

Developing information concerning phosphatic clay properties and methods of disposal and reclamation has been a research priority on the Institute's list. Therefore, the Institute granted funds (FIPR #8O-02-003) to develop a data base on the chemical composition, mineralogy, and mechanical properties of phosphatic clays. In another project (FIPR #81-02-017) the U.S. Bureau of Mines studied state-of-the-at? of phosphatic research and phosphatic clay disposal.

Field evaluation of currently used disposal and reclamation methods is considered of prime importance in the Institute's research program. In this regard, the Institute supported two studies (FIPR 80-03-006 and FIPR #83-02-038) constituting a two-phase project to monitor and evaluate the performance of sand-clay mix reclamation at CF Industries' Hardee County Phosphate Complex and to obtain field data on the long-term settling and consolidation characteristics of sand-clay mixes in order, ultimately, to evaluate the reclamation qualities of this method. In another project (FIPR #84-03-054) a comprehensive geotechnical and hydrological evaluation of sand-clay mixing as practiced by Brewster Phosphates was completed.

The Florida Institute of Phosphate Research has a continuous interest in new techniques tackling problems associated with phosphatic clays. In this respect, the Institute has sponsored research dealing with disposal of phosphatic clays in mine cuts (FIPR #81-03-006) in which instruments were placed in a full-scale mine cut disposal area to monitor the in-place consolidation of the clay, desiccation of the formed crust and the performance of any soil cap. The data were used in developed computer programs to analyze two-dimensional finite strain consolidation.

Thermal dewatering of phosphatic clay waste was the subject of a study (FIPR #82-02-021) to determine if the freeze-melt method, using butane as a reagent, could be used to remove water from phosphatic clays.

A laboratory, as well as a field test program, was funded by the Institute (FIPR #82-02-021) to study improvements in sedimentation rate and strength of phosphatic clays, and to identify areas of practical application in phosphatic clay disposal and reclamation.

New reclamation methods are also in the Institute's perspective, as demonstrated by funding a project (FIPR # 82-02-030) to cap a full-scale mine cut with a high ratio sand-clay mix and to utilize extensive centrifuge testing of phosphatic clays to determine their rate of settling in consolidation under various conditions.

The Institute has been pursuing every avenue that might lead to the solution of phosphatic clay problems. This is shown by in-house research project (FIPR #82-02-040R) in which the causes of water retention in clays were investigated. In addition, different methods of stabilizing and hardening the clays using lime, phosphogypsum and other hardening agents were studied.

This report represents Volume 7 of a complementary series of volumes resulting from the work sponsored by the Institute (FIPR #80-02-002 and FIPR #83-02-042). As part of Phase I (FIPR #80-02-002), a comprehensive study to evaluate the engineering properties of a wide range of phosphatic clays and sand-clay mixes, and develop a methodology for forecasting the performance of phosphatic clay settling areas during disposal and reclamation was conducted. The findings of the Phase I study were presented in a series of six complementary volumes.

Laboratory evaluations of the engineering properties of phosphatic clays and sand-clay mixes were performed on phosphatic clays from twelve different mine sites. Volumes 1, 2 and 3 titled "Index Properties of Phosphatic Clays," "Mineralogy of Phosphatic Clays," and "Sedimentation

Behavior of Phosphatic Clays," respectively, presented extensive data on the twelve clay sources selected in the study. The findings were used to screen the samples and select six clays covering the full range of anticipated behavioral characteristics. The selected clays were subjected to a comprehensive testing program for determing engineering parameters pertaining to consolidation and strength. Extensive sophisticated testing of three of the six phosphatic clays and corresponding sand-clay mixes was subsequently undertaken. The results were presented in Volumes 4 and 5 titled "Consolidation Behavior of Phosphatic Clays" and "Shear Strength Characteristics of Phosphatic Clays," respectively.

Concurrent with the laboratory evaluations of phosphatic clay engineering properties, a theoretical model to evaluate disposal systems was developed. The finite difference program SLURRY can also be used in reclamation planning. In an attempt to verify and refine the prediction modeling technique, a preliminary field investigation program at five conventional phosphatic clay settling areas and one sand-clay mix settling area ranging from retired to active sites was undertaken. Volume 6 titled "Predictive Methodology for Evaluating Disposal Methods" presented results of the field investigation program, and evaluated the theoretical predictive model. This report (Vol. 7) includes the engineering properties of flocculated phosphatic clays, which is part of the currently funded Phase II (FIPR #83-02-042).

Although flocculated clays are being experimentally evaluated for disposal, both alone and in conjunction with the sand-clay mix at several mine sites, there is surprisingly a very limited amount of comprehensive data on the engineering properties of flocculated phosphatic clays.

One of the objectives of this Phase II study is to determine the range of settling and consolidation properties of flocculated phosphatic clays with known mineralogic composition and physical characteristics (such as plasticity and grain size) to help mine planners evaluate their disposal method based on the clay mineralogy and index properties at a particular mine. Another objective is to use the range of established properties for flocculated clays and incorporate this recently developed dewatering method in the evaluation of phosphatic clay disposal and reclamation methods. As part of these evaluations, a laboratory testing program was performed to characterize the shear strength of flocculated clays in order to determine whether this disposal method would result in areas of poor, marginal or good foundation conditions.

The results obtained in this part of the study indicate that flocculation does not have a major effect on the stress-strain strength behavior, effective angles of internal friction, and normalized, undrained Young's decant modules. However, a very slight effect of flocculation on the normalized and undrained shear strength ratio was noted for normally consolidated phosphatic clays. Those findings, coupled with the results of the following tasks, will be of great help to mine planners in evaluating their disposal methods.

The data obtained thus far from this project and other projects described above, suggest that there is still a wide area for further research to achieve an ultimate solution of the phosphatic clays problem.

EVALUATION OF PHOSPHATIC CLAY DISPOSAL AND RECLAMATION METHODS

Research Projects FIPR 80-02-002
and FIPR 83-02-042

PREFACE

As part of a Florida Institute of Phosphate Research project FIPR 80-02-002 titled “Evaluation of Phosphatic Clay Disposal and Reclamation Methods”, Ardaman & Associates, Inc. performed a comprehensive study to evaluate the engineering properties of a wide range of phosphatic clays and sand-clay mixes, and developed a methodology for forecasting the performance of phosphatic clay settling areas during disposal and reclamation. The findings of the Phase I study (Research Project FIPR 80-02-002) were presented in a series of six complementary volumes. Subsequently, a Phase II study was initiated (Research Project FIPR 83-02-042) to evaluate the engineering properties of flocculated phosphatic clays, refine the predictive capability, and compare and evaluate the relative merits of various disposal methods on the basis of parametric studies illustrated via an example of a model mine. Findings from the Phase II study are presented in a series of four additional volumes.

Laboratory evaluations of the engineering properties of phosphatic clays and sand-clay mixes were performed on phosphatic clays from twelve different mine sites. Volumes 1, 2 and 3 titled “Index Properties of Phosphatic Clays", “Mineralogy of Phosphatic Clays", and "Sedimentation Behavior of Phosphatic Clays”, respectively, present extensive data on the twelve clay sources selected in the study. The findings were used to screen the samples and select six clays covering the full range of anticipated behavioral characteristics. The selected clays were subjected to a comprehensive testing program for determining engineering parameters pertaining to consolidation and strength. Extensive sophisticated testing of three of the six phosphatic clays and corresponding sand-clay mixes was subsequently undertaken. The results are presented in Volumes 4 and 5 titled “Consolidation Behavior of Phosphatic Clays" and “Shear Strength Characteristics of Phosphatic Clays”, respectively.

Concurrent with the laboratory evaluation of phosphatic clay engineering properties, a theoretical model to evaluate disposal systems was developed. The finite difference program SLURRY can also be used in reclamation planning. In an attempt to verify and refine the prediction modeling technique, a preliminary field investigation program at six phosphatic clay settling areas ranging from retired to active sites was undertaken. Volume 6 discusses the theoretical model and presents a comparison of predictions based on laboratory data and field measurements.

To allow evaluation of flocculated clay disposal methods in addition to the conventional and sand-clay mix disposal methods, a laboratory testing program was undertaken in the Phase II study on three flocculated phosphatic clays. The three clays were selected based upon the Phase I findings to cover the full range of anticipated behavioral characteristics. Laboratory testing consisting of evaluations of index properties, settling and consolidation behavior, and shear strength properties -were subsequently undertaken. The results are presented in Volume 7 titled "Engineering Properties of Flocculated Phosphatic Clays".

Results from the Phase II field testing program performed to refine the predictive capability for three selected sites utilizing conventional, sand-clay mix, and flocculated clay disposal methods are presented in Volume 8 titled “Predictive Methodology Applied to Case Histories”. Predictions from laboratory data and program SLURRY are compared with field measurements for each disposal area.

A user’s manual for a refined version of program SLURRY is presented in Volume 9 titled “Program SLURRY-User’s Manual?‘. The theoretical background, layout and algorithm for the model is discussed, a program listing is given, and several sample problems illustrating the capabilities of the program are presented.

Evaluation of the relative merits of various phosphatic clay disposal and reclamation methods is made in Volume 10 on the basis of parametric studies illustrated via an example of a model mine.

EVALUATION OF PHOSPHATIC CLAY
DISPOSAL AND RECLAMATION METHODS

Volume 7: Engineering Properties of
Flocculated Phosphatic Clays

Research Project FIPR 83-02-042
Final Report, December 1985

ABSTRACT

The index properties, settling and consolidation behavior, and shear strength characteristics of three phosphatic clays flocced with a commercially available flocculant are presented and compared with properties of unflocced clays. The specific Agrico-Saddle Creek, USSAC-Rockland and CF Mining-Hardee phosphatic clays sampled during the Phase I study were selected for the investigation. These three clays were previously found to be characteristic of high, average and relatively low plasticity phosphatic clays, respectively, with differing mineralogy, and settling and consolidation properties which bracketed the range of behavioral characteristics reported for unflocced phosphatic clays.

The flocculated phosphatic clays were prepared using NALCO 7877 flocculant. The NALCO 7877 flocculant is an acrylamide polymer emulsion containing 29% polymer solids by dry weight. The flocculant is reportedly used with phosphatic clays at loading rates of 0.3 to 1.2 pounds of polymer per ton of clay. For this investigation, the flocculant was added to clay suspensions in one increment as a 0.1% solution by volume.

The results from laboratory settling tests on phosphatic clays with an initial solids content of 3% indicated that, as expected, flocculation significantly increased initial settling rates by two to three orders of magnitude. Clays of higher plasticity, however, required a higher flocculant loading rate to achieve the same relative increase in initial settling rate. A maximum initial settling rate was attained for a given clay at an “optimum” flocculant loading rate beyond which the addition of more flocculant was detrimental and produced lower initial settling rates. The “optimum” flocculant loading rate for NALCO 7877 increased from 0.60 pounds of polymer per ton of clay for relatively low plasticity phosphatic clays to 2.4 pounds per ton of clay for relatively high plasticity phosphatic clay. Additional tests performed at initial solids contents of 1% and 8% using the “optimum” flocculant loading rate (determined for an initial solids content of 3%), indicated that

the initial settling rate was significantly increased for clay with an initial solids content of 1% but only slightly affected for clay with an initial solids content of 8%. Further, excessive or too little mixing during flocculation and remixing after flocculation were found to adversely affect initial settling rates due to poor floe formation and/or breaking-up of the floes. Little effect due to mixing technique, however, was observed on the "final" settled solids content.

Clays which settled to relatively low solids contents naturally were also found to settle to relatively low solids contents with flocculation. Low to medium plasticity phosphatic clays were actually found to display a modest to slight decrease in "final" settled solids content when flocced, with the magnitude of the decrease increasing with increasing flocculant loading rate. Conversely, high plasticity phosphatic clays were found to display a very slight increase in "final" settled solids when flocced. Hence, the laboratory settling tests indicated that the only benefit of flocculation was to improve the initial settling rate.

The behavior of the artificially flocced phosphatic clays was generally consistent with the Michaels and Bolger (1.962) theory for the settling behavior of flocculated clay suspensions. The Michaels and Bolger methodology, therefore, was used to extrapolate results from the laboratory settling tests in a limited size container to the field scale of an "infinite size container". At 3% initial solids content, the field initial settling rate for flocced clays was found via the Michaels and Bolger (1962) methodology to be up to two times faster than inferred from laboratory scale initial settling rates. Laboratory settling rates, therefore, should be increased when predicting field settling rates to account for the laboratory effects of a limited size container. Further, the "final" settled solids contents to be anticipated in the field were extrapolated via the Michaels and Bolger (1962) methodology to be slightly greater than inferred from laboratory "final" settled solids contents.

Slurry consolidation tests performed on flocculated phosphatic clays indicated a range of effects of flocculation on consolidation behavior. Most importantly, the assumption of a unique void ratio versus effective stress relationship for flocced and unflocced clays was determined not to be always justified. The experimental data indicate that relatively high plasticity phosphatic clays may display a unique relationship, but low to medium plasticity phosphatic clays may yield a higher void ratio at a given effective stress when flocced than when unflocced.

The concept of a unique void ratio versus coefficient of permeability relationship for flocced and unflocced clays was found to be reasonably justified. Deviations from the unique relationship at a given void ratio were relatively small, but tended to increase with decreasing clay plasticity. At a given effective stress, however, the coefficient of permeability of a flocced clay tends to be somewhat higher than that of an unflocced clay.

The coefficient of consolidation, c_v, of flocced and unflocced phosphatic clays at a given effective stress are similar for high plasticity clays. The coefficient of consolidation is moderately higher for medium to low plasticity flocced clays than characteristic for unflocced clay. Somewhat higher coefficients of consolidation occur because the coefficients of permeability of the flocced clays at a given effective stress are slightly greater than for unflocced clays. As a guide, average coefficients of consolidation in the range of $2x10^{-4}$ to $4x10^{-4}$ cm^2/sec should be typical for a wide range of flocced clays.

The coefficient of secondary compression of flocced phosphatic clays displayed no correlation with plasticity or monotonic trends with effective stress. As a general guideline, a coefficient of secondary compression for flocced clays of 1.4%$\pm$0.6% appears reasonable. This value is somewhat higher than found for unflocced phosphatic clays.

The results from $\overline{CIUC}$ tests indicate that the undrained effective stress paths and stress-strain behavior of normally consolidated flocced and unflocced clays are similar. Hence, flocculation does not have a major effect on the stress-strain-strength behavior of phosphatic clays. Further, the effective stress paths and stress-strain behavior support the applicability of the normalized soil parameter concept to flocced phosphatic clays.

A very slight effect of flocculation on the normalized undrained shear strength ratio, $s_u/\bar{\sigma}_{vc}$, was noted for normally consolidated phosphatic clays. Overall, however, $s_u/\bar{\sigma}_{vc}$ from $\overline{CIUC}$ tests appears similar for all flocced and unflocced clays with a representative value of 0.28 being applicable for normally consolidated phosphatic clays.

Effective angles of internal friction, $\bar{\phi}$, determined at maximum obliquity and at maximum stress difference for flocced and unflocced clays were not significantly different. For drained effective stress type stability analyses an effective angle of internal friction, $\bar{\phi}_d$, of 23^o was found characteristic for normally consolidated flocced clays.

As with unflocced phosphatic clays, the undrained Young's secant modulus of flocced clays was determined to be highly stress-level dependent. No consistent effects of flocculation on the normalized undrained Young's secant modulus, E_u/s_u, however, were observed. Overall, the average E_u/s_u versus stress level relationship developed for unflocced clays also appears reasonable for flocced clays.

ACKNOWLEDGEMENTS

The support and sponsorship provided by the Florida Institute of Phosphate Research to conduct this investigation is gratefully acknowledged. The permission, cooperation and assistance provided by Agrico Chemical Company, CF Mining Corporation, Gardinier, Inc., United States Steel Corporation Agrichemicals Division and their representatives to allow publication of information and access to disposal areas for sampling and field testing is greatly appreciated.

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LIST OF SYMBOLS

Symbol	Description
INDEX AND CLASSIFICATION PROPERTIES	
A	Activity of a Clay
CH	Clay of High Plasticity
CL	Clay of Low Plasticity
FLR	Flocculant Loading Rate
LL	Liquid Limit
PI	Plasticity Index
PL	Plastic Limit
S	Solids Content
w_n	Natural Moisture Content
ρ	Specific Gravity
γ_d	Dry Density
γ_t	Total Unit Weight
γ_w	Unit Weight of Water
SETTLING RATE AND SOLIDS CONTENT PROPERTIES	
b	Ordinate Intercept of $Z_o\phi_K$ vs. Z_F
C_{AK}	Ratio of ϕ_A/ϕ_K
$\bar{d}_A$	Average Equivalent Aggregate Diameter
e	Void Ratio
e_f	Final Void Ratio
g	Gravitational Acceleration
H_F	Height of Clay Flocs
Q	Settling Rate of Slurry-Supernatant Interface
Q_o	Laboratory Initial Settling Rate
Q'_o	Field Initial Settling Rate
Q_s	Average Secant Settling Rate
Q_1	Maximum Laboratory Settling Rate

LIST OF SYMBOLS
(continued)

Symbol	Description
S	Solids Content
S_{fl}	Solids Content of Flocculant
S_i	Initial Solids Content
S_{if}	Initial Flocced Clay Solids Content
S_F	Final Solids Content
t	Time
t_1	Time of Maximum Settling Rate
t_s	Time Selected to Calculate Q_s
V_{SA}	Stoke's Settling Velocity
Z	Height of Slurry-Supernatant Interface
Z_o	Initial Height of Slurry-Supernatant Interface
Z_{of}	Initial Height of Flocced Slurry-Supernatant Interface
Z_F	Final Height of Slurry-Supernatant Interface
Z_s	Height Selected to Calculate Q_s
μ_w	Absolute Viscosity of Water
ϕA	Aggregate Volume Concentration
ϕF	Floc Volume Concentration
ϕK	Clay Volume Concentration
ρ_w	Supernatant Specific Gravity

COMPRESSIBILITY AND PERMEABILITY PARAMETERS

Symbol	Description
c_v	Coefficient of Consolidation
$c_v(\sqrt{t})$	Coefficient of Consolidation from Square Root of Time Method
$C\alpha$	Coefficient of Secondary Compression
e	Void Ratio
e_i	Initial Void Ratio for Consolidation
e_f	Final Void Ratio at End of Settling
e_{50}	Void Ratio at 50% Consolidation
e_{100}	Void Ratio at 100% Consolidation
k	Coefficient of Permeability
k_c	Calculated Coefficient of Permeability
k_f	Coefficient of Permeability for Flocced Clay
k_m	Measured Coefficient of Permeability
$k(\sqrt{t})$	Coefficient of Permeability Backfigured from Square Root of Time Method
k_{uf}	Coefficient of Permeability for Unflocced Clay

LIST OF SYMBOLS
(continued)

Symbol	Description
m_v	Coefficient of Volume Change
$\bar{U}$	Percent Consolidation
α	Linear Regression Coefficient in Effective Stress Compressibility Equation or Z ϕ_K Versus Z_F Equation
β	Exponent Regression Coefficient in Effective Stress Compressibility Equation
γ	Linear Regression Coefficient in Permeability/Void Ratio Equation
γ_w	Unit Weight of Water
δ	Exponent Regression Coefficient in Permeability/Void Ratio Equation
$\bar{\sigma}$	Effective Stress
$\bar{\sigma}_{vc}$	Effective Vertical Consolidation Stress
$\bar{\sigma}_{vm}$	Maximum Past Vertical Effective Consolidation Stress

STRESS, STRAIN, MODULUS AND STRENGTH PARAMETERS

Prefix Δ indicates a change or an increment.
Suffix "f" indicates a final or failure condition.
Subscript "o" indicates an initial condition.
A bar over a stress indicates an effective stress.
A bar over a property indicates value in terms of effective stress.
A bar over a test indicates that pore pressures were measured.

Symbol	Description
A	Skempton's Pore Pressure A-Factor
$\bar{c}$	Intercept of Mohr-Coulomb Failure Envelope or Effective Cohesion Intercept
E_u	Undrained Young's Secant Modulus
E_{u50}	E_u at Stress Level of 50%
K_o	Coefficient of Lateral Earth Pressure at Rest = $\bar{\sigma}_{vh}/\bar{\sigma}_{vc}$
$\bar{p}$	Average Effective Principal Stress = 0.5 $(\bar{\sigma}_1+\bar{\sigma}_3)$
q	Half Principal Stress Difference = 0.5 $(\sigma_1-\sigma_3)$ = Maximum Shear Stress
q_f	q at Failure = Maximum q
Δq_f	Increment of Shear Stress to Cause Failure

LIST OF SYMBOLS
(continued)

Symbol	Description
s_u	Undrained Shear Strength
$s_u(V)$	Undrained Shear Strength with Major Principal Stress in Vertical Direction
u	Pore Pressure
ε	Linear or Axial Strain
ε_v	Vertical Strain
$\sigma, \bar{\sigma}$	Normal Total Stress, Normal Effective Stress
$\sigma_1, \sigma_2, \sigma_3$	Principal Stresses (major, intermediate and minor, respectively)
$\bar{\sigma}_c$	Effective Isotropic Consolidation Pressure
$\bar{\sigma}_{hc}$	Effective Horizontal Consolidation Stress (normal)
$\sigma_v, \bar{\sigma}_v$	Vertical Normal Stress, Vertical Normal Effective Stress
$\bar{\sigma}_{vc}$	Effective Vertical Consolidation Stress
$\bar{\sigma}_{vo}$	Initial Vertical Effective Stress
$\bar{\phi}$	Slope of Mohr-Coulomb Failure Envelope or Effective Angle of Internal Friction
$\bar{\phi}_d$	$\bar{\phi}$ from Drained Tests
ϕ_u	$\bar{\phi}$ from Undrained Tests

MISCELLANEOUS

Symbol	Description
$\overline{CIU}C$	Isotropically Consolidated Undrained Triaxial Compression Test
NSP	Normalized Soil Parameters
r	Correlation Coefficient

Section 1

RESEARCH BACKGROUND AND OBJECTIVES

1.1 Introduction

As part of Phase I of research project FIPR 80-02-002 "Evaluation of Phosphatic Clay Disposal and Reclamation Methods", a comprehensive laboratory testing program was undertaken on phosphatic clays and sand-clay mixes sampled at twelve settling areas and/or pilot plants. The sampling sites were selected to provide a range of geographic locations (and, therefore, potentially clay types) and mining concerns. Figure l-l illustrates the locations of the selected mine sites.

The laboratory testing program performed as part of the Phase I study included evaluations of index properties, mineralogic composition, settling and consolidation behavior, and shear strength properties of phosphatic clays and sand-clay mixes. The results and findings of the laboratory testing were previously presented in a series of five complementary volumes, Volume 1 through 5. The objective of these tests was to comprehensively assess engineering properties of phosphatic clays and sand-clay mixes for use in evaluating and comparing conventional and sand-clay mix disposal methods. To extend these evaluations and comparisons to allow consideration of the flocculated clay disposal method, an additional laboratory testing program was performed on flocculated phosphatic clays including evaluations of index properties, settling and consolidation behavior, and shear strength properties. The results of this additional laboratory testing are presented herein.

1.2 Purpose of Investigation

Although flocculated phosphatic clays are being experimentally evaluated both alone and in conjunction with the sand-clay mix disposal method at several mine sites, there is a limited amount of reported data on the engineering properties of flocculated clays. Generally, as reported by Bromwell (1984), the primary benefit of flocculation is to reduce the time for sedimentation to occur. Limited consolidation test results suggest that subsequent to sedimentation, the compressibility and permeability of flocced and unflocced phosphatic clays may be the same.

There is a lack of reported engineering properties for a range of flocculated phosphatic clays where the mineralogic composition, index properties, settling and consolidation characteristics, and shear strength behavior of the parent phosphatic clays are well established. Accordingly, as part of research project FIPR 83-02-042 "Evaluation of Phosphatic Clay Disposal and Reclamation Methods" - Phase II performed for the Florida Institute of Phosphate Research, three phosphatic clays previously found to be representative of the range of behavioral characteristics reported for phosphatic clays were selected for evaluation.

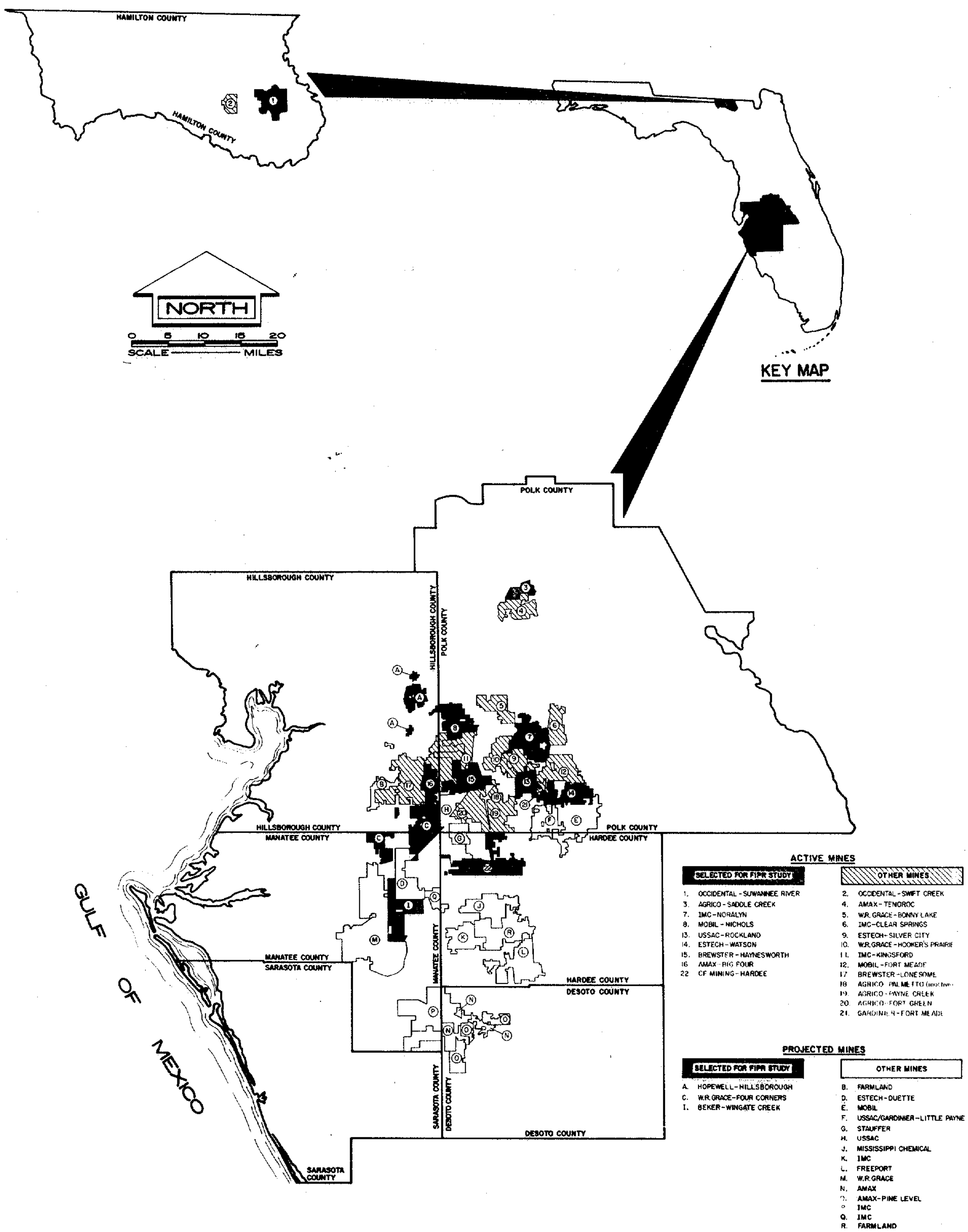
The purpose of the investigation, therefore, was to first determine the index properties, settling and consolidation behavior, and shear strength characteristics of the three selected phosphatic clays flocced with a commercially available flocculant, and secondly to compare the properties of the flocced and unflocced clays to evaluate the effects of flocculation. Once developed, the engineering properties of the flocculated clays can be used in conjunction with the previously established clay and sand-clay mix properties to evaluate conventional, sand-clay mix and flocculated clay disposal methods for a given clay.

1.3 Scope of Investigation

The scope of investigation included determining the engineering properties of three flocculated phosphatic clays. The specific Agrico-Saddle Creek, CF Mining-Hardee and USSAC-Rockland phosphatic clays sampled during the Phase I study were previously found to be characteristic of high, average and relatively low plasticity phosphatic clays, respectively, with substantially differing mineralogy, settling, and consolidation behavior that bracketed the range of behavioral characteristics reported for phosphatic clays. Accordingly, these three phosphatic clays were selected for flocculation to characterize the range of index, settling, consolidation and shear strength properties of flocculated clays.

The index properties of the selected phosphatic clays, the flocculated clays, and the flocculant are discussed in Section 2. The solids content, plasticity characteristics, particle size distribution, specific gravity and activity of each clay are considered. In Section 3, the settling characteristics of each flocculated clay are presented. A total of over 50 settling tests were performed to establish: the effect of flocculant loading rate on settling behavior; the effect of mixing during and after flocculation; and physical parameters of the flocculated suspension interpreted in accordance with the Michaels and Bolger (1962) methodology. Further, the settling behavior of the flocced clays is compared to the previously established behavior of the unflocced clays (Volume 3) to determine the effects of flocculation on settling behavior and "final" settled solids content.

Results from slurry consolidation tests performed on each phosphatic clay flocculated at the "optimum" flocculant loading rate are presented in Section 4. The void ratio (or solids content) versus effective stress (e vs. $\bar{\sigma}_{vc}$), coefficient of consolidation versus effective stress (c_v vs. $\bar{\sigma}_{vc}$), and coefficient of permeability versus void ratio (k vs. e) relationships are discussed and compared to the previously established relationships (Volume 4) for unflocced clay. Correlations showing the effect of flocculation on the consolidation properties of clays of various plasticity are presented to allow potential qualitative extrapolation of the test results to other phosphatic clays. Finally, in Section 5 the effects of flocculation on the shear strength properties of normally consolidated phosphatic clays are evaluated via consolidated undrained triaxial compression tests with pore pressure measurements ($\overline{\text{CIU}}$C tests). The normalized undrained shear strength ratio ($s_u/\bar{\sigma}_{vc}$), effective friction angle ($\bar{\phi}$), and normalized undrained Young's secant modulus ratio (E_u/s_u) of the flocculated clays are established and compared to previously reported relationships (Volume 5) for unflocced clay.



MINE SITES SELECTED FOR INVESTIGATION

FIGURE 1-1

Section 2

INDEX PROPERTIES OF FLOCCULATED PHOSPHATIC CLAYS AND FLOCCULANT CHARACTERISTICS

2.1 Introduction

The index properties of the three phosphatic clays and characteristics of the flocculant selected for evaluation of the engineering properties of flocculated phosphatic clays are presented in this section. The clays selected for evaluation and the index properties of the phosphatic clays sampled for Phase II testing are first compared to the index properties previously established for the Phase I clays. The characteristics of the selected flocculant are then addressed. Finally, the index properties of the flocculated clays are considered.

2.2 Selection of Phosphatic Clays for Evaluation

The specific Agrico-Saddle Creek, CF Mining-Hardee and USSAC-Rockland phosphatic clays sampled during the Phase I study were previously found to be characteristic of high, average and relatively low plasticity phosphatic clays, respectively, with substantially differing mineralogy, settling, and consolidation behavior. Further, the engineering properties of these clays were found to cover the full range of behavioral characteristics typically reported for phosphatic clays. Accordingly, these three phosphatic clays were selected to evaluate the effects of flocculation on the engineering properties of phosphatic clays. It is expected that since the selected clays are representative of the range of behavioral characteristics of unflocced clays, that they also will be similarly representative of the range of behavioral characteristics of flocced clays.

2.3 Sample Collection

Samples of phosphatic clay were obtained for the Phase II testing at approximately the same general sampling locations as previously selected for the Phase I study. At Agrico-Saddle Creek Settling Area 2 and USSAC-Rockland Settling Area 6 several samples were obtained within each area from recently settled clay not yet subjected to desiccation. Several locations were selected in an attempt to obtain clay identical to that tested during the Phase I study. At CF Mining-Hardee Settling Area N-l the Phase II samples were obtained from one location within the settled clays via the dredge which removes settled clay from the area for mixing with sand to produce sand-clay mix.

Sampling of the phosphatic clays was performed on March 28 and April 11, 1984. A total of nine 5 gallon containers of phosphatic clay were collected from the three selected settling areas. Six 5 gallon containers of pond water were also collected from USSAC-Rockland Settling Area 6 for use in preparation of diluted laboratory test specimens.

2.4 Comparison of Index Properties and Settling Characteristics of Phase I and Phase II Phosphatic Clays

The index properties and settling characteristics of the Phase II phosphatic clay samples were determined for comparison with the Phase I samples to verify that the selected clays were identical. The index properties measured included the plasticity characteristics (Atterberg limits), particle size distribution, specific gravity and activity. A series of settling tests were also performed to verify that the laboratory settling rates and "final" settled solids contents of the selected clays were similar.

2.4.1 Plasticity Characteristics

The plasticity characteristics of each sample were determined via Atterberg limits performed to confirm that the selected clays were identical to those used in the Phase I study. A significant variability was exhibited by the clays obtained from some settling areas, particularly Agrico-Saddle Creek Settling Area 2. Nevertheless, clay samples were found which satisfactorily matched the plasticity of the clays used in the Phase I study. The sampled solids content and Atterberg limits are presented in Table 2-1 along with the previously reported (Volume 1) sampled solids content and plasticity characteristics for the Phase I clays. Figure 2-1 compares the plasticity of the Phase I and Phase II phosphatic clays from each mine. As shown, the plasticity of the selected Phase II phosphatic clays agrees well with the plasticity of the previously investigated Phase I phosphatic clays.

2.4.2 Particle Size Distribution

The particle size distributions of the Phase II phosphatic clays were determined using seive and hydrometer analyses (with sodium hexametaphosphate as a dispersant). Sieve analyses were performed for particle sizes greater than 74 µm. Since Stoke's Law is used to interpret the hydrometer analyses, which describes the settling behavior of spherical particles, the resulting particle size distributions actually represent equivalent particle diameters.

The particle size distributions of the selected Phase II clays are presented in Figures 2-2 through 2-4 and compared with particle size distributions previously reported for the Phase I clays. As shown, the selected Agrico and USSAC clays display almost identical particle size distributions and clay size particle fractions, where the clay size particle fraction is defined as the percentage of material by dry weight finer than the 2 µm size. The selected Phase II CF Mining-Hardee clay is slightly finer than the Phase I clay.

2.4.3 Activity

The engineering properties of clays are influenced by the type of clay minerals and the amount of clay present. The relative influence of these two factors on the engineering behavior of a clay can be qualitatively evaluated by the activity of a clay, which is defined as the ratio of the plasticity index, PI, to the clay size particle fraction, -2 µm (Skempton, 1953). As shown in Figure 2-5, the relation between plasticity index and clay fraction for a given clay mineral is a straight line passing through the origin. Generally, the higher the activity of a clay, the more important the influence of the clay fraction on the engineering properties of the soil.

Clay minerals have different activities as shown in Figure 2-5. Smectite clay minerals have activities ranging from 1 to 7 with the most active smectite (sodium montmorillonite) having activities ranging from 3.0 to 7.2. Calcium montmorillonite typically has an activity of 1.3. Palygorskite, illite, and kaolinite have activities of 1.2, 0.9 and 0.4, respectively.

The activities of the selected Phase II clays are presented in Figure 2-5 and compared with the activities previously reported for the Phase I clays. As shown, the Phase I and Phase II Agrico and USSAC clays display essentially identical activities of 3.2 and 2.1, respectively. The Phase II CF Mining-Hardee clay displays a slightly lower activity than the Phase I clay due to the higher clay particle size fraction.

2.4.4 Specific Gravity

The measured specific gravities of each of the selected phosphatic clays are presented below:

Sample	Specific Gravity, p	
	Phase I	Phase II
Agrico-Saddle Creek	2.788	2.774
CF Mining-Hardee	2.807	2.816
USSAC-Rockland	2.812	2.767

The measured specific gravities of the Phase I and Phase II clays are similar. For reference, the specific gravity of minerals commonly found in phosphatic clays are: smectite (2.78); illite (2.61); palygorskite (2.09); kaolinite (2.61); apatite (3.20); dolomite (2.85); and quartz (2.66).*

2.4.5 Representative Index Properties

The representative index properties selected for each Phase II phosphatic clay are summarized in Table 2-2 along with representative properties previously established for the Phase I clays. As shown, the index properties of the Phase I and Phase II clays agree well, with the largest deviation, for any property occurring in the clay size particle fraction of the CF Mining-Hardee phosphatic clay. Accordingly, based on index properties the selected Phase II clays are judged essentially identical to the Phase I clays. The representative index properties selected for each clay are recommended for use in establishing correlations and extrapolating test results to other clays.

*Refer to Volume 2, Section 3 for a detailed discussion of specific gravity and corresponding mineralogic composition for the clay and non-clay minerals present in phosphatic clays.

2.4.6 Settling Characteristics

A series of settling tests were performed on the selected Phase II phosphatic clays to verify that the settling behavior and "final" settled solids contents were similar to those previously established for the Phase I clays.* The laboratory settling tests were performed in plexiglass graduated settling "columns" 10.4 cm in diameter and 30.5 cm high in accordance with procedures previously described in Volume 3, Section 2.3. An initial solids content, S_i, of 3% and initial sample height, Z_o, of 24 cm were used for each test.

2.4.6.1 "Final" Settled Solids Content

The settling test results are graphically summarized as height of interface versus time and solids content versus log time for each sample in Figures 2-6 and 2-7, respectively. As shown, the Phase I and Phase II phosphatic clays display similar settling behavior and "final" settled solids contents, S_F. The Phase I and Phase II "final" settled solids contents were 5.4% and 6.2% for the Agrico clay, 17.8% and 15.8% for the CF clay, and 9.3% and 8.4% for the USSAC clay. As shown in Figure 2-8, the differences between the "final" settled solids contents for each individual clay are relatively small considering the range of "final" settled solids contents exhibited by the three clays. Accordingly, based upon "final" settled solids contents the Phase II clays are judged essentially identical to the Phase I clays.

2.4.6.2 Laboratory Settling Rate

The maximum laboratory settling rates, Q_1, measured on the Phase II phosphatic clays are summarized in Table 2-3 and compared with previously established settling rates for the Phase I clays. As shown, the maximum laboratory settling rates are similar for the Phase I and Phase II phosphatic clays and vary from 0.11-0.16 cm/hour for the Agrico clay, from 5.5 to 8.4 cm/hour for the CF clay, and from 0.32-0.83 cm/hour for the USSAC clay.

The maximum laboratory settling rate is an instantaneous settling rate that occurs relatively early in the settling test in comparison to the time required to achieve the "final" settled solids content. Table 2-3 presents the time at which the maximum settling rate occurs, t_l, and the solids content at this time, S_1, for both the Phase I and Phase II clays. The times at which the maximum settling rates occur for the Phase I and Phase II clays are also compared in Figure 2-9. As shown, the times of maximum settling rates are similar for the Phase I and Phase II clays and decrease for clays with higher settling rates and higher "final" settled solids contents. The Phase I and Phase II clays also display similar solids contents at the time of the maximum settling rate (Table 2-3), which generally vary from 3.2% for the Agrico clay, to 3.3% for the USSAC clay, to 3.8% for the CF clay.

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*Refer to Volume 3, Section 3.2 for a description of the Phase I clay "final" settled solids contents and settling rates.

While the maximum laboratory settling rate is of interest to characterize the settling behavior of phosphatic clays, the average settling rate from the initial to "final" solids content is more appropriately represented by the average secant settling rate, Q_S. The average secant settling rate is the slope of the line between the initial and "final" height of the interface plotted versus time. For determining the average secant settling rate the "final" height and time were defined at the intersection of the linear portion of the tail end of the height of interface versus time curve with the initial curved portion of the settling curve (Figure 2-6). Table 2-3 presents the average secant settling rates determined for an initial solids content of 3% and the time, t_S, and height, Z_s, of the "final" clay interface selected to calculate the secant settling rates. As shown, the average secant settling rates are similar for the Phase I and Phase II clays and range from 0.026 to 0.065 cm/hour.

Based upon both the maximum laboratory settling rate and average secant settling rate, the Phase I and Phase II clays are judged essentially identical.

2.5 Flocculant Selection and Relevant Characteristics

Selection of a flocculant for testing was guided by the reported flocculants being used in Florida on phosphatic clays. Estech is using several polyacrylamide flocculants at their Watson mine in conjunction with a flocculated sand-clay mix disposal method. NALCO 7877 flocculant is one of the flocculants being used by Estech, and is commercially available. Gardinier, Inc., at their Fort Meade Mine, conducted a flocculated clay disposal demonstration project from March 1962 through September 1993. During this period they evaluated 30 different flocculants from several manufacturers. No specific flocculant was preferred by Gardinier, Inc. and the loading rates used were proprietary. Other mining concerns are not currently investigating flocculants, although experiments have been performed by some (e.g., Mobil).

Accordingly, for preparation of flocculated phosphatic clays, the NALCO 7877 flocculant was selected. The NALCO 7877 flocculant is an acrylamide polymer emulsion containing 29% polymer solids by dry weight. The emulsion weighs 8.7 pounds per gallon and is reportedly used with phosphatic clays at loading rates of 0.3 to 1.2 pounds of polymer per ton of clay. A potential user forecasting a need for not less than 1,500,000 pounds of emulsion would reportedly pay on the order of $0.65 per pound for the emulsion, including shipping costs.

2.6 Index Properties of Flocculated Phosphatic Clays

The plasticity characteristics of each phosphatic clay after flocculation were determined via Atterberg limits on samples prepared at various flocculant loading rates. The Atterberg limits were performed on samples at an initial solids content of 3% flocced in one step at the stated loading rate using a 0.10% solution by volume of NALCO 7877 flocculant and subsequently allowed to settle for a period of about 30 days. The clear supernatent was then removed and the tests were performed on the settled suspension. Generally, flocculated clays are expected to yield a higher liquid limit than unflocced clays due to the formation of more edge to face particle contacts, which normally results in an increase in the strength and "rigidity" of a suspension. However, remolding during testing can destroy the gain in strength resulting from flocculation.

The liquid limits measured on each sample at various flocculant loading rates are depicted in Figure 2-10. As shown, although there is some variability in the results, there is a general weak trend of increasing liquid limit with increasing flocculant loading rate for the CF and USSAC clays. The increase in liquid limit is relatively small, being on the order of 10% at a flocculant loading rate of 1.5 lb/ton of clay. The liquid limit of the Agrico flocculated clay displayed the unexpected behavior of a general decrease in liquid limit on the order of 10%.

Table 2-1

PLASTICITY OF PHOSPHATIC CLAYS

Mine	Sample	Sampling Date	Average Sampled Solids Content S (%)	LL (%)	PL (%)	PI (%)
• **PHASE I SAMPLES**						
Agrico-Saddle Creek	Settling Area 2	01-28-81	6.6	280	41	239
Agrico-Saddle Creek	Settling Area 2	06-05-81	7.6	255	50	205
Agrico-Saddle Creek	Settling Area 2	06-05-81	7.6	236	47	189
CF Mining-Hardee	Settling Area N-1	12-08-80	24.8	154	33	121
CF Mining-Hardee	Settling Area N-1	01-28-81	8.4	139	31	108
CF Mining-Hardee	Settling Area N-1	06-05-81	30.9	137	26	111
USSAC-Rockland	Settling Area 6	01-28-81	11.0	200	34	166
USSAC-Rockland	Settling Area 6	01-28-81	11.0	211	38	173
USSAC-Rockland	Settling Area 6	01-28-81	11.0	196	38	158
USSAC-Rockland	Settling Area 6	01-28-81	11.0	191	36	155
• **PHASE II SAMPLES**						
Agrico-Saddle Creek	Settling Area 2	03-28-84	20.5	173	53	120
Agrico-Saddle Creek	Settling Area 2	03-28-84	30.4	191	53	138
Agrico-Saddle Creek	Settling Area 2	04-11-84*	16.9	291	66	225
Agrico-Saddle Creek	Settling Area 2	04-11-84	26.7	141	45	96
Agrico-Saddle Creek	Settling Area 2	04-11-84	30.6	182	45	137
CF Mining-Hardee	Settling Area N-1	03-28-84*	15.8	154	36	118
USSAC-Rockland	Settling Area 6	03-28-84	20.0	238	49	189
USSAC-Rockland	Settling Area 6	03-28-84	19.1	229	56	173
USSAC-Rockland	Settling Area 6	03-28-84*	18.0	207	49	158

*Selected Phase II samples used for evaluation of flocculated clay.
Where: LL = Liquid limit; PL = Plastic limit; and PI = Plasticity index

Table 2-2

REPRESENTATIVE INDEX PROPERTIES OF SELECTED PHOSPHATIC CLAYS

Mine	Sample	Sampling Date	Plasticity LL (%)	Plasticity PI (%)	Clay Fraction -2 μm (%)	Activity A	Specific Gravity ρ
• **Agrico-Saddle Creek**	**Settling Area 2**						
	Phase I	01-28-81	268	222	71	3.13	2.788
	Phase II	04-11-84	291	225	67	3.36	2.774
• **CF Mining-Hardee**	**Settling Area N-1**						
	Phase I	01-28-81	143	113	57	1.98	2.807
	Phase II	03-28-84	154	118	76	1.55	2.816
• **USSAC-Rockland**	**Settling Area 6**						
	Phase I	01-28-81	195	160	78	2.05	2.812
	Phase II	03-28-84	207	158	77	2.05	2.767

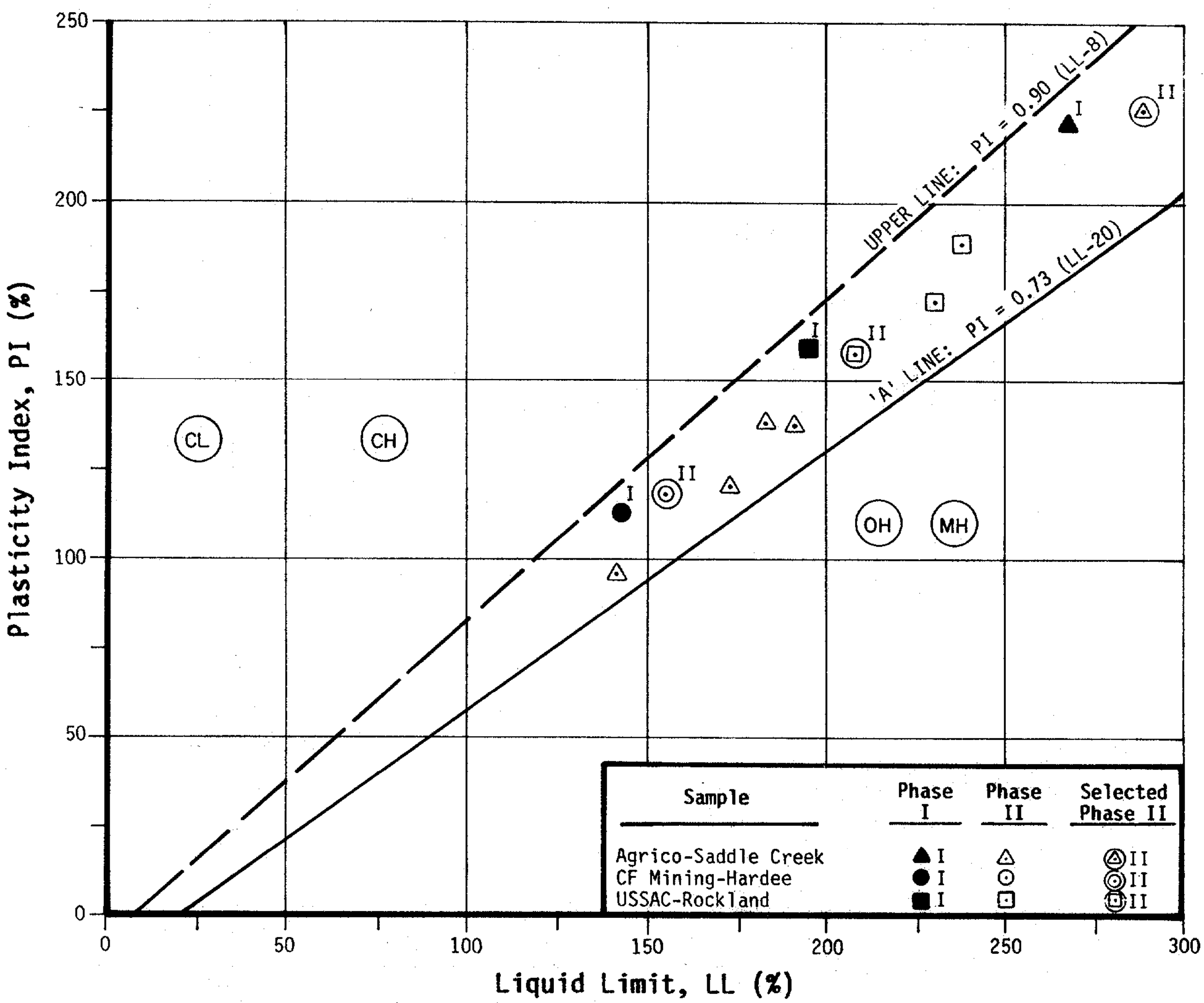
Where: LL = Liquid Limit and PI = Plasticity Index

Table 2-3

SETTLING CHARACTERISTICS OF SELECTED PHOSPHATIC CLAYS

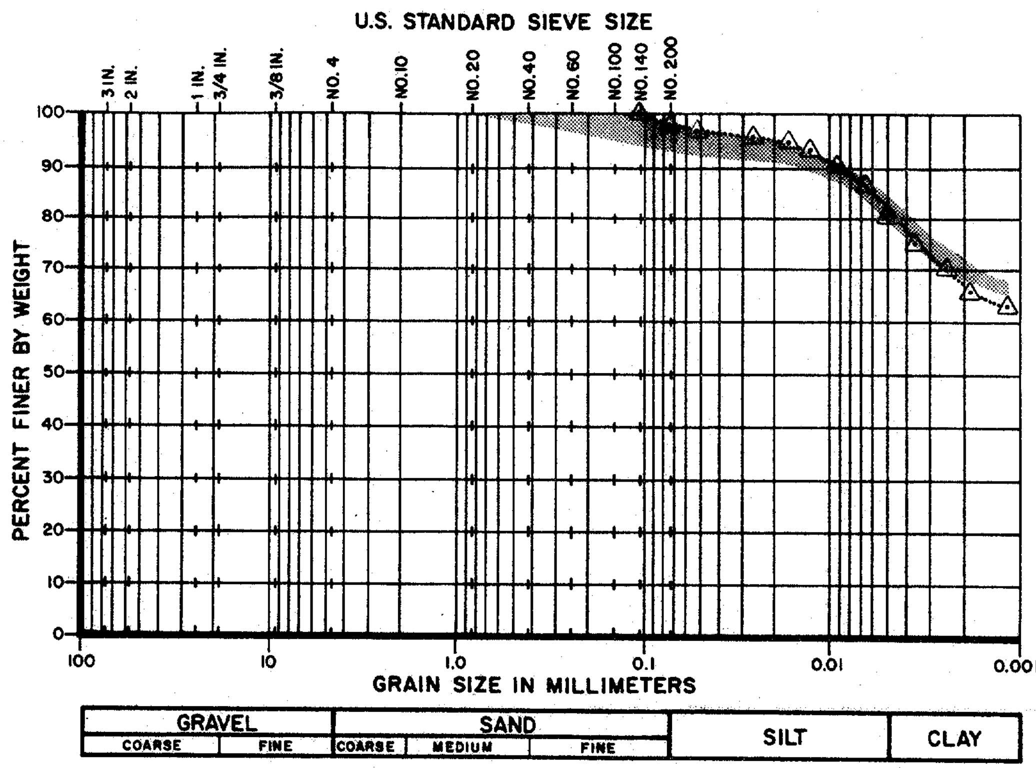
Mine	Sample	Sampling Date	Initial Solids Content S_i(%)	"Final" Settled Solids Content S_F(%)	Maximum Settling Rate Q_1 (cm/hour)	t_1 (min)	S_1 (%)	Secant Settling Rate Q_s (cm/hour)	t_s (min)	Z_s (cm)
• **Agrico-Saddle Creek**	**Settling Area 2**									
	Phase I	01-28-81	3.0	5.4	0.156	900	3.20	0.026	24,700	13.5
	Phase II	04-11-84	3.0	6.2	0.110	750	3.15	0.030	24,500	11.7
• **CF Mining-Hardee**	**Settling Area N-1**									
	Phase I	01-28-81	3.0	17.8	8.44	50	3.71	0.065	18,700	3.8
	Phase II	03-28-84	3.0	15.8	5.45	100	3.99	0.063	18,500	4.6
• **USSAC-Rockland**	**Settling Area 6**									
	Phase I	01-28-81	3.0	9.3	0.834	900	3.45	0.055	17,500	8.0
	Phase II	03-28-84	3.0	8.4	0.318	450	3.25	0.048	18,700	9.1

Where: Q_1 = Maximum laboratory settling rate; t_1 = Time of maximum settling rate; S_1 = Settled solids content at time of maximum settling rate; Q_s = Average secant settling rate; t_s = Time selected to calculate Q_s; Z_s = Height of clay interface selected to calculate Q_s.



PLASTICITY OF SELECTED PHOSPHATIC CLAYS

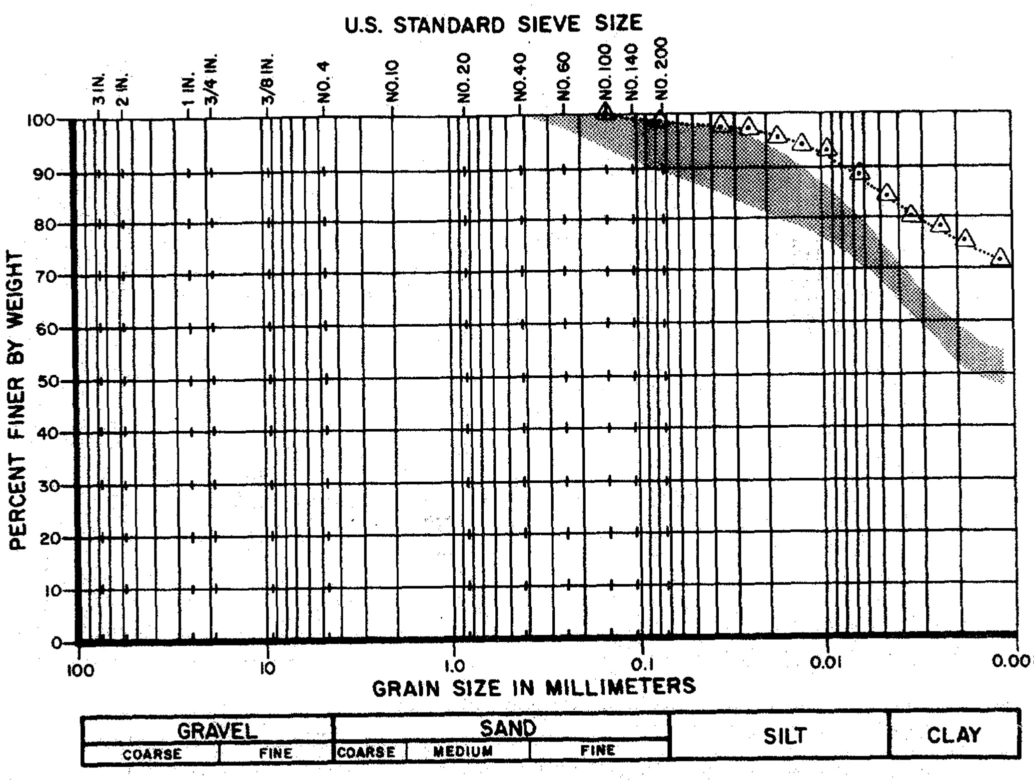
FIGURE 2-1



Symbol	Description	Clay Fraction, -2µm (%)
(shaded)	Phase I	71
△	Phase II	67

PARTICLE SIZE DISTRIBUTION OF AGRICO-SADDLE CREEK PHOSPHATIC CLAY

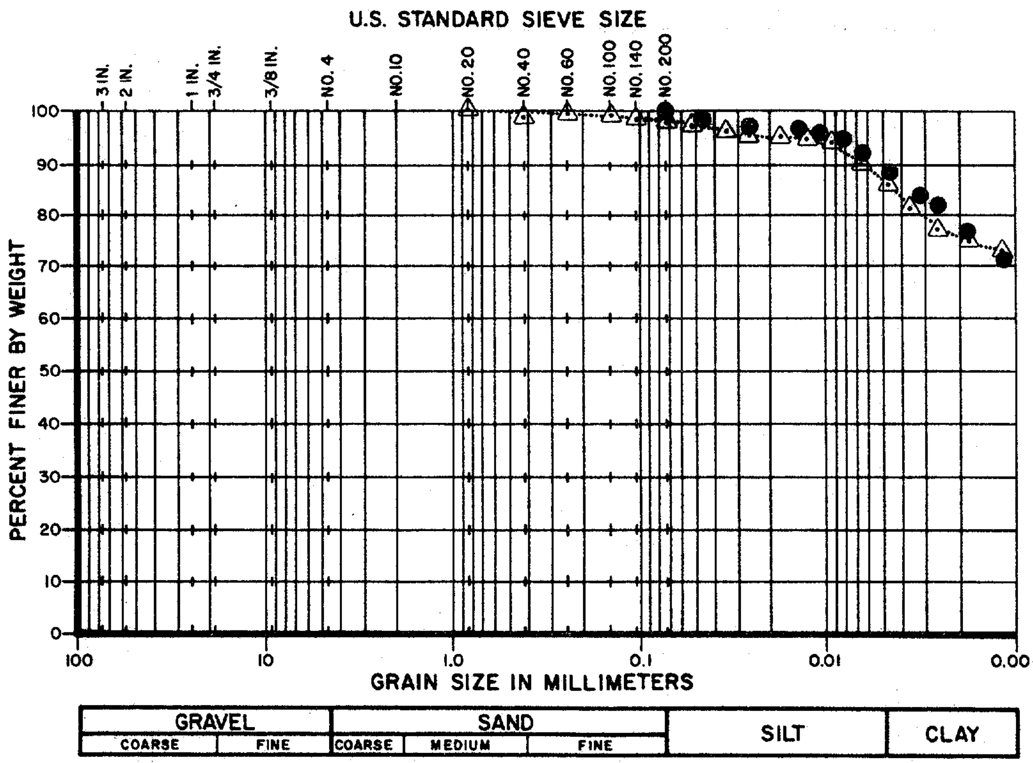
FIGURE 2-2



Symbol	Description	Clay Fraction, -2μm (%)
(shaded band)	Phase I	57
△	Phase II	76

PARTICLE SIZE DISTRIBUTION OF CF MINING-HARDEE PHOSPHATIC CLAY

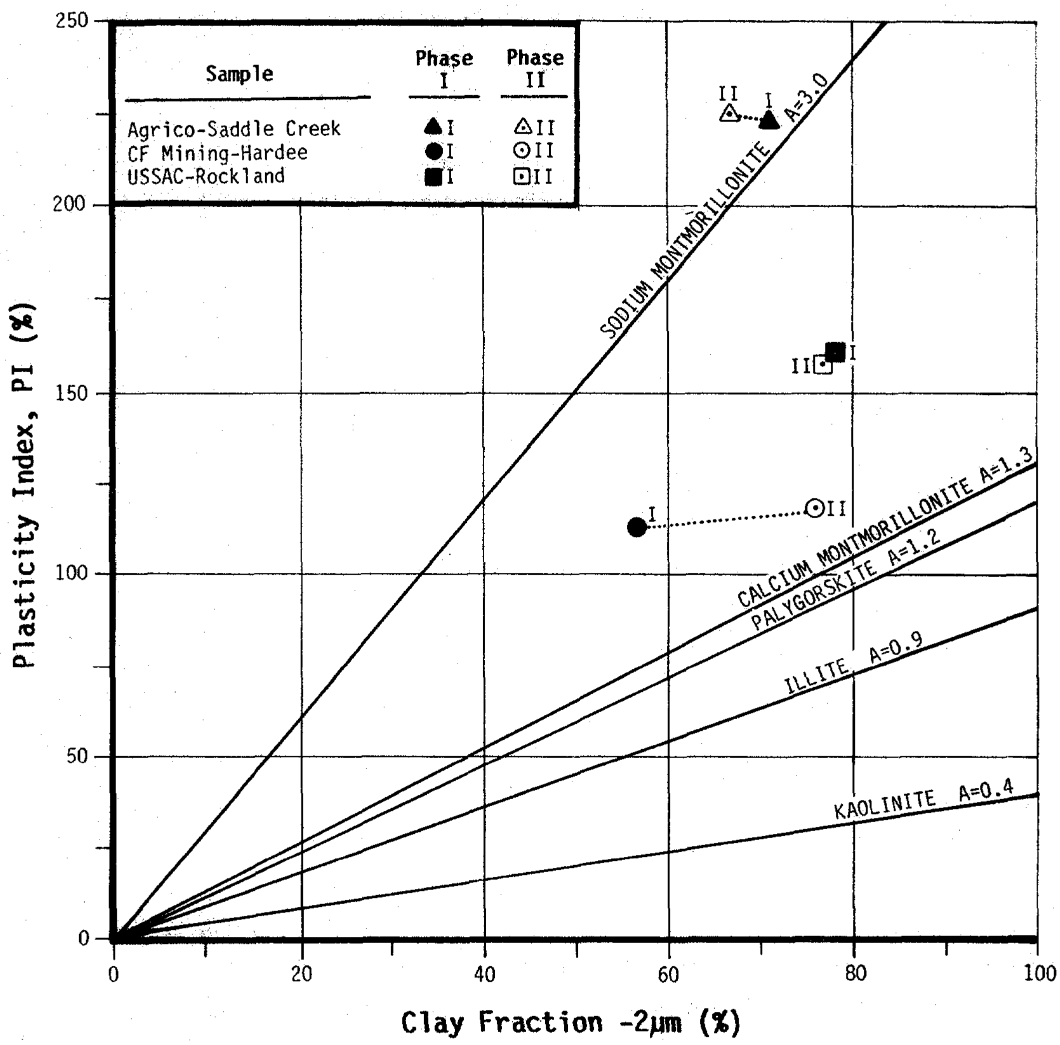
FIGURE 2-3



Symbol	Description	Clay Fraction, -2μm (%)
●	Phase I	78
△	Phase II	77

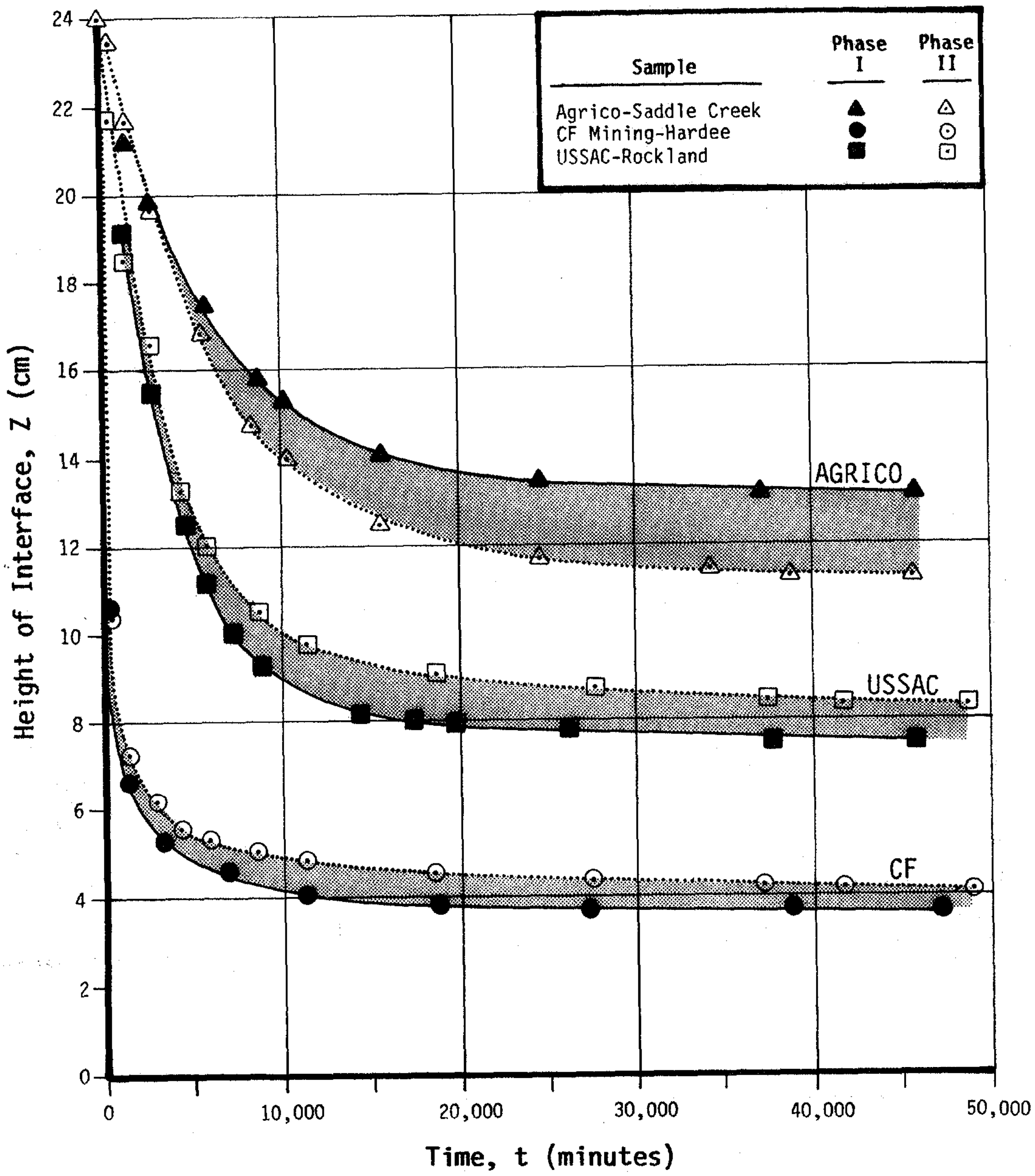
PARTICLE SIZE DISTRIBUTION OF USSAC-ROCKLAND PHOSPHATIC CLAY

FIGURE 2-4



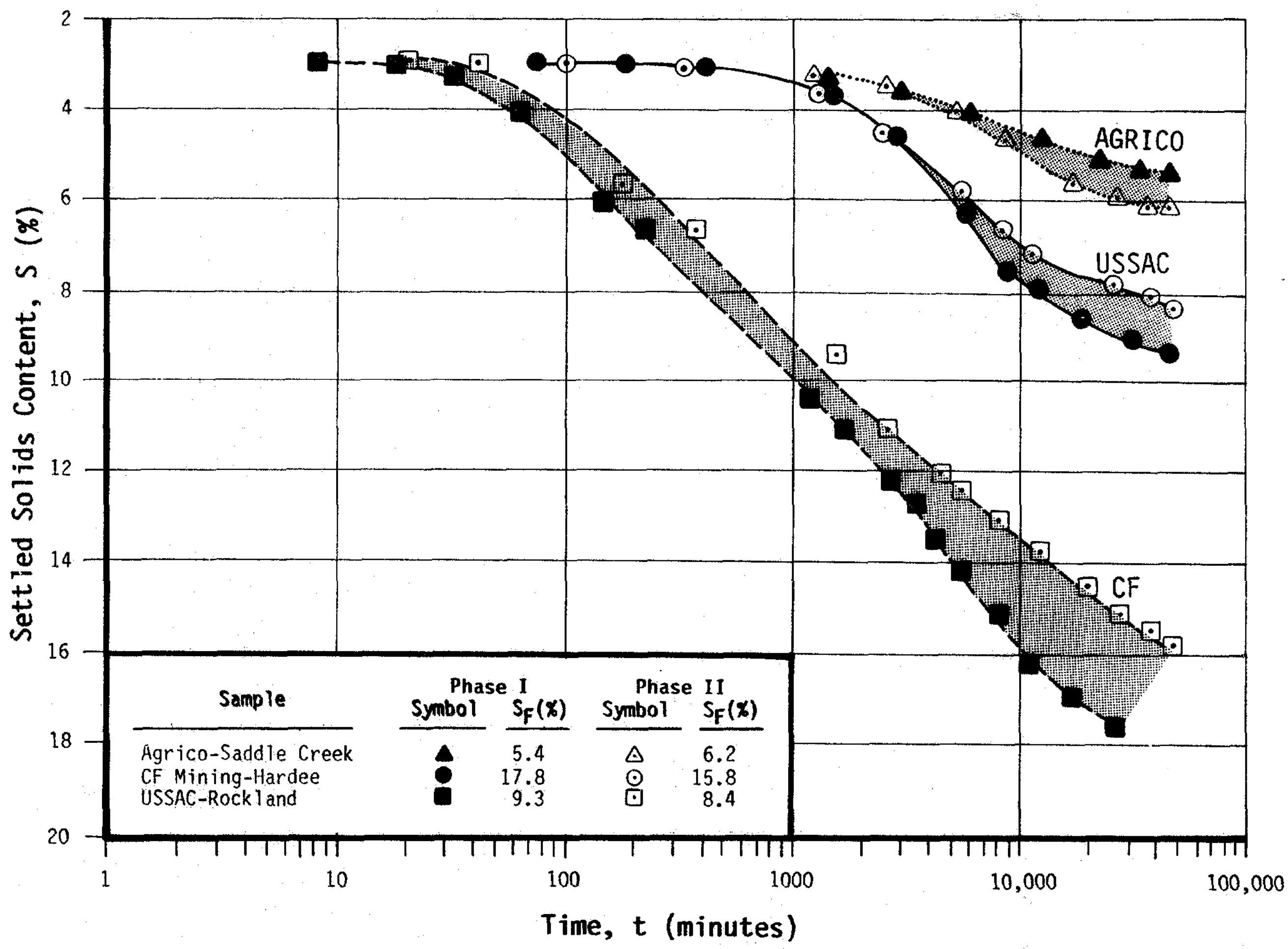
ACTIVITY OF SELECTED PHOSPHATIC CLAYS

FIGURE 2-5



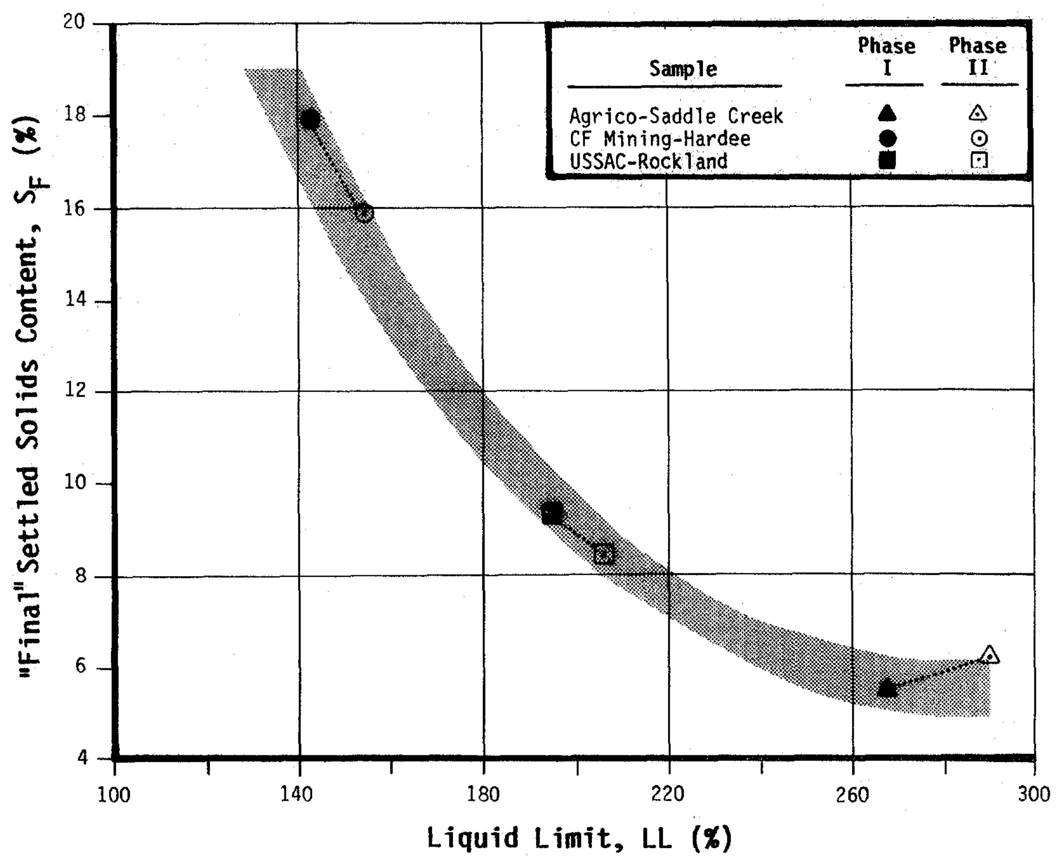
SETTLING TEST HEIGHT VS. TIME FOR SELECTED PHOSPHATIC CLAYS AT 3% INITIAL SOLIDS CONTENT

FIGURE 2-6



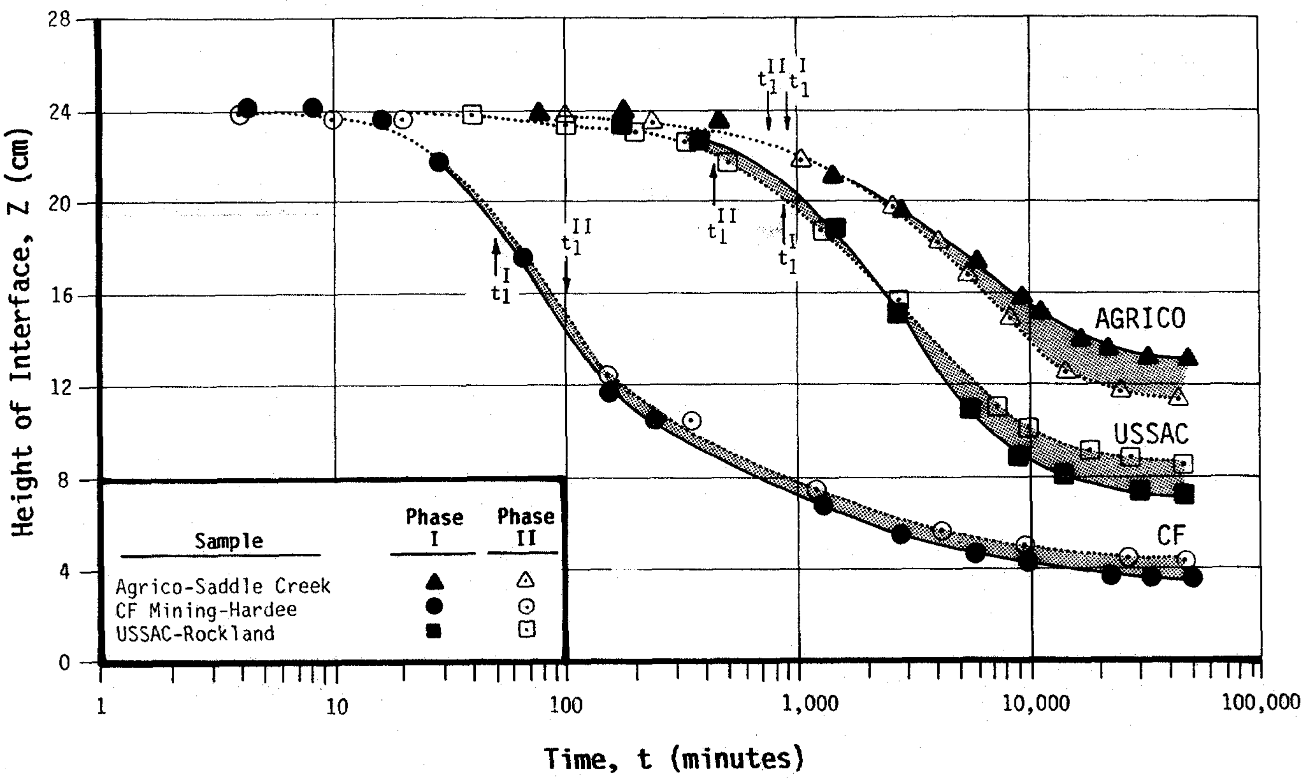
SETTLING TEST SOLIDS CONTENT VS. LOG TIME FOR SELECTED PHOSPHATIC CLAYS AT 3% INITIAL SOLIDS CONTENT

FIGURE 2-7



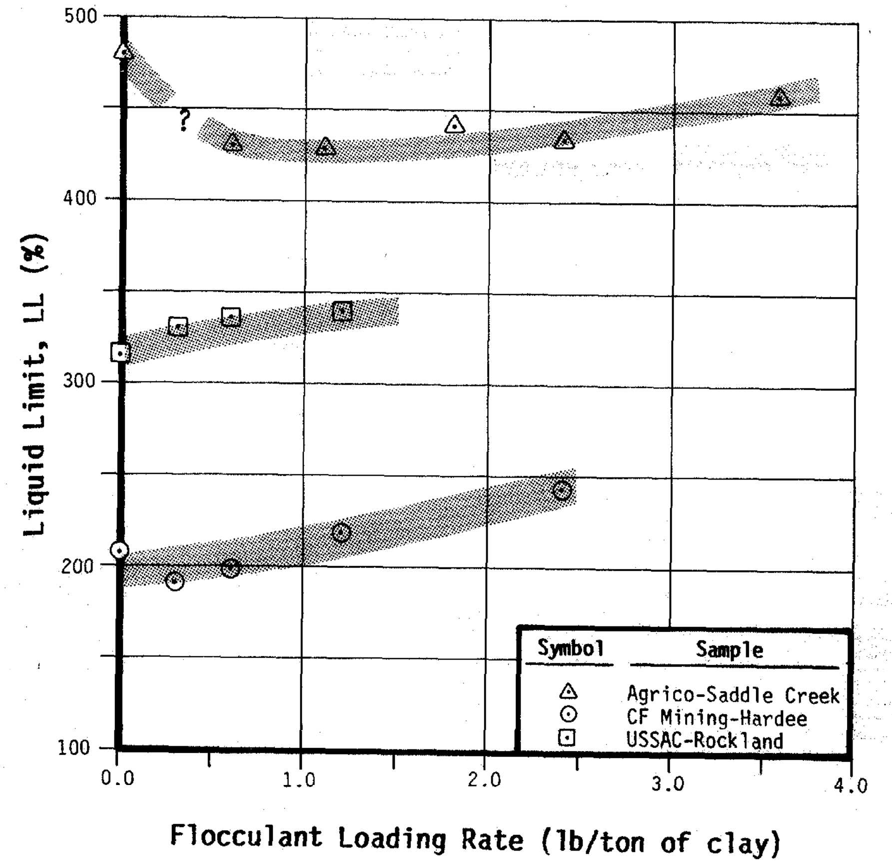
LIQUID LIMIT VS. "FINAL" SETTLED SOLIDS CONTENT FOR SELECTED PHOSPHATIC CLAYS

FIGURE 2-8



TIME FOR MAXIMUM LABORATORY SETTLING RATE FOR SELECTED PHOSPHATIC CLAYS AT 3% INITIAL SOLIDS CONTENT

FIGURE 2-9



EFFECT OF FLOCCULANT ON PLASTICITY OF PHOSPHATIC CLAYS

FIGURE 2-10

Section 3

SEDIMENTATION BEHAVIOR OF FLOCCULATED PHOSPHATIC CLAYS

3.1 Introduction

Little published data is reported on the sedimentation behavior of flocculated phosphatic clays. Since the flocculated clay disposal method is potentially a feasible disposal alternative, at least at some mine sites, the sedimentation characteristics of flocculated clays are of interest. The objective of the present investigation on the sedimentation behavior of flocculated clays, therefore, was to determine the effect of flocculant loading rate on settling behavior and on the “final” settled solids content, and the physical parameters of the flocculated clay suspension interpreted in accordance with the Michaels and Bolger (1962) methodology. To achieve this objective, over 50 laboratory settling tests were performed on three selected phosphatic clays with varying flocculant loading rates.

All settling tests performed on flocculated clays are presented and evaluated in this section. As discussed in Section 1, phosphatic clays from the Agrico, CF and USSAC mines were selected for the flocculated clay settling tests. These three clays are representative of relatively poor, good and average settling clays, respectively, and should indicate the effect of flocculation on the range of phosphatic clays likely to occur. Various initial clay solids contents and flocculant loading rates were used to determine the effect of these factors on the settling behavior of flocculated clays.

3.2 Experimental Scheme

Four series of laboratory settling tests were performed to evaluate various aspects of the sedimentation behavior of flocculated phosphatic clays, namely:

- The effect of flocculant loading rate on settling behavior and "final" settled solids content, and selection of an “optimum” flocculant loading rate.
- The effect of initial solids content on the settling behavior of clays flocced at the optimum flocculant loading rate.
- The effect of mixing during and after flocculation on settling behavior.
- The extrapolation of laboratory settling behavior obtained in a “limited” size container to the field situation of an “infinite” size container via the Michaels and Bolger (1962) methodology.

Constant initial height settling tests were performed on each clay at an initial solids content of 3% to investigate the effect of flocculant loading rate on settling behavior, "final" settled solids content, and to allow selection of an "optimum" flocculant loading rate for each clay. These tests were performed from an initial height, Z_o, of 24 cm in 10.4 cm diameter settling "columns". Flocculant loading rates 0.3 to 3.6 lb/ton of clay were used.

The effect of initial solids content on settling behavior was investigated for each clay at initial solids contents of 1%, 3% and 8% flocced at the selected "optimum" flocculant loading rate. These tests were performed from an initial height of 24 cm in 10.4 cm diameter settling "columns".

The effect of mixing during and after flocculation on settling behavior was evaluated for each clay at an initial solids content of 3% flocced at the "optimum" flocculant loading rate. The effects of mixing during flocculation and remixing after initial settling were investigated.

Variable initial height settling tests were performed on each clay at initial solids contents of 3% and 8% flocced at the "optimum" flocculant loading rate. Initial heights of 6, 12, 18 and 24 cm were used. Results from these tests were interpreted to: obtain parameters describing the settling characteristics of flocculated clay suspensions in accordance with the Michaels and Bolger (1962) methodology; and to establish the void ratio (or solids content) versus effective stress compressibility curve at very low effective stresses.

3.3 Test Methods, Procedures and Nomenclature

Laboratory settling tests were performed in plexiglass graduated settling "columns" 10.4 cm in diameter and 30.5 cm high in accordance with the general procedures previously described in Volume 3, Section 2.3. The variable initial height settling tests were evaluated via the Michaels and Bolger (1962) methodology as previously outlined in Volume 3, Section 2.4.

3.3.1 Test Methods and Procedures

After preparing a clay sample to the desired initial solids content, the clay slurry was poured into the settling "column" to a desired initial sample height. The clay was thoroughly mixed after placement within the column with a hand-held perforated plunger type stirrer to provide a homogeneous sample. The stirrer was then removed and a pre-measured quantity of NALCO 7877 flocculant was added to the suspension in one increment. The stirrer was replaced into the column after addition of the flocculant and the suspension was slowly "stroked" up and down until the maximum effect of the flocculant (i.e., floc size) was visually observed, typically after 6 to 12 strokes in 10 to 15 seconds. The stirrer was then removed and the height of the interface with time was monitored.

As recommended by the manufacturer, the flocculant was added to the clay suspension as a 0.1% solution by volume. The flocculant was prepared into a 0.1% solution from the as-received emulsion as follows:

- Homogenize the as-received sample by mixing until uniform in appearance.

- Add 10 ml of emulsion to 990 ml of tap water to produce a 1.0% solution by volume. The 10 ml of emulsion was injected with a disposable syringe into 990 ml of tap water in a mixer with a propeller type impeller. The mixer was operated for 15 minutes at 800 to 1500 revolutions per minute (rpm) to maintain a vortex within the solution.

- The 1.0% solution was used to produce 0.1% solution as needed for testing by mixing desired amounts of tap water with the 1.0% solution. Hand shaking was used to homogenize the 0.1% solution prior to addition to a clay suspension.

The shelf life of the 1.0% solution was taken as 5 days as recommended by the manufacturer. Accordingly, new 1.0% solution was made weekly as needed for testing. The 1.0% solution was refrigerated between use and the 0.1% solution was mixed on the day needed for testing.

At the reported emulsion weight of 8.7 lb/gallon and active polymer solids content of 29%, each 10 ml of emulsion weighed 10.43 grams and contained 3.03 grams of active polymer. Accordingly, for floccing laboratory samples each 10 ml of 1% solution was assumed to contain 0.0303 grams of active polymer and each 10 ml of 0.1% solution was assumed to contain 0.00303 grams of active polymer.

3.3.2 Nomenclature

For flocculated clays it is useful to define the initial solids content of the clay both prior to and after flocculation, since water is added to the system during the addition of flocculant. The initial unflocced clay solids content, S_i, and initial flocced day solids content, S_{if}, are related by the expression:

$$S_{if} = S_{fl} / ((S_{fl} / S_i) + FLR) \qquad (1)$$

where: S_{fl} is the solids content of flocculant as added to the clay suspension; and FLR is the flocculant loading in units of weight of polymer solids to weight of clay solids. For NALCO 7877 flocculant at an as-received solids content of 29% and weight of 8.7 lb/gallon added in a 0.10% solution the flocculant solids content, S_{fl}, is 0.03023%.

3.4 Effect of Flocculation on Settling Behavior and "Final" Settled Solids Content

Results from constant initial height settling tests on the three selected phosphatic clays at 3% initial solids content flocced at various flocculant loading rates are summarized in Appendix C, Figures C-l through C-6. Solids content versus log time and height of interface versus time plots are presented in these figures for each clay and flocculant loading rate. Pertinent results and relevant data for each test are summarized in Table 3-1.

3.4.1 **Final** Settled Solids Content

The "final" settled solids content, S_F, achieved for various flocculant loading rates are summarized in Table 3-1 and in Figure 3-1. As with clay and sand-clay mix settling tests, the flocculated clay settling tests indicate significant variability in the “final” settled solids content of the various flocculated phosphatic clays. For an initial clay solids content of 3% and flocculant loading rate of 1.2 lb/ton of clay, the “final” solids contents are generally lower than for the unflocced clay and range from 6.2% for the Agrico clay, to 8.0% for USSAC clay, to 13.0% for the CF clay. The settling tests also indicate that a clay which settles to a relatively low “final” solids content without flocculation, also settles to a relatively low “final” solids content with flocculation, although at high flocculant loading rates it appears that the “final” settled solids contents of the medium to high plasticity phosphatic clays (i.e., USSAC and Agrico clays, respectively) begin to approach a similar value of 6.5%.

In general, a flocculated clay is expected to yield slightly lower settled solids contents than an unflocced clay due to the formation of larger flocs. As shown in Figure 3-1, this behavior was observed for the low to medium plasticity CF and USSAC phosphatic clays, which at a flocculant loading rate of 1.2 lb/ton of clay displayed reductions in the “final” settled solids content from 15.8% to 13.0% and from 8.4% to 8.0% respectively. Conversely, the highly plastic Agrico phosphatic clay displayed a small increase in “final" solids content with increasing flocculant loading rate. It appears that relatively low to medium plasticity phosphatic clays display a lower “final” settled solids content after flocculation in comparison to unflocced clay, with the magnitude of the reduction increasing with decreasing clay plasticity and increasing flocculant loading rate. As shown in Figure 3-2, the “final” solids content ratio* varies from 0.75 to 0.85 at a plasticity index of 120% for flocculant loading rates of 2.0 to 0.50 lb/ton of clay, but equals about 1.0 for loading rates of interest at a plasticity index of 200%.

3.4.2 Laboratory Settling Rate

The initial laboratory settling rates, Q_o, achieved at various flocculant loading rates are summarized in Table 3-1 and in Figure 3-3. Individual height of interface versus time plots for each flocculated clay during the initial stages of settling used to obtain the initial settling rate are presented in Figures 3-4, 3-5 and 3-6. Flocculation should increase the initial settling rate because of the formation of larger flocs than exist naturally in the phosphatic clays. Typically, large flocs result in higher settling rates. As expected, the addition of flocculant results in significant increases in the initial settling rate of the phosphatic clays with increases of two to three orders of magnitude achieved at flocculant loading rates of 0.3 to 2.4 lb/ton of clay.

As shown in Figure 3-7, for loading rates less than about 1.5 lb/ton of clay, the more highly plastic clays display less of a relative increase in settling rate than the lower plasticity clays at the same flocculant loading rate. At higher flocculant loading rates (i.e., above 1.5 lb/ton of clay) the highly plastic clays display a larger relative increase in the settling rate although the actual value of

*Where the “final” solids content ratio is defined as the ratio of S_F for the flocced clay at a given flocculant loading rate to S_F for the unflocced clay.

the initial settling rate may still be lower. In comparing the three clays, however, the clay that was relatively slow to settle without flocculation (i.e., Agrico) was still always relatively slow to settle with flocculation (Figure 3-3).

The settling tests also indicate that a maximum initial settling rate is attained beyond which higher flocculant loading rates produce lower initial settling rates. For the Agrico, CF and USSAC clays, the maximum initial settling rate was achieved at flocculant loading rates of 2.4, 1.2 and 2.4 lb/ton of clay, respectively.

3.4.3 Selection of Optimum Flocculant Loading Rate

The "optimum" flocculant loading rate for each clay was selected as the flocculant loading rate which produced the maximum settled solids content, S, and secant settling rate, Q_s, at an arbitrarily selected time of 100 minutes. The settled solids content and secant settling rate at 100 minutes are summarized in Table 3-1 and in Figure 3-8.

As shown in Figure 3-8, the "optimum" flocculant loading rate increases with increasing clay plasticity and was selected as 0.6 lb/ton of clay for the CF clay, 1.2 lb/ton of clay for the USSAC clay and 2.4 lb/ton of clay for the Agrico clay. The relationship between the clay plasticity index and selected "optimum" flocculant loading rate is presented in Figure 3-9. The relationship is essentially linear over the range of plasticity index from 120 to 225% and indicates that an additional 0.17 lb/ton of clay of flocculant is needed to achieve the "optimum" flocculant loading rate for each 10% increase in plasticity index, beginning at 0.6 lb/ton of clay at a plasticity index of 120%.

3.5 Effect of Initial Solids Content on Settling Behavior and "Final" Settled Solids Content at "Optimum" Flocculant Loading Rate

The effect of initial solids content on the settling behavior of phosphatic clays flocced at the "optimum" flocculant loading rate was determined for initial solids contents of 1%, 3% and 8%. Results from the settling tests are presented as solids content versus log time and height of interface versus time in Appendix D, Figures D-l through D-6. Individual test results and relevant data are summarized in Appendix A, Tables A-l through A-3.

3.5.1 "Final" Settled Solids Content

The "final" settled solids content achieved for each clay, both flocced and unflocced, for initial solids contents of 1%, 3% and 8% are summarized below and in Figure 3-10.

Parameter	Sample		
	Agrico Saddle Creek	CF Mining Hardee	USSAC Rockland
Initial Solids Content, S_i=1%			
S_F(Flocced), %	5.6	13.3	7.1
S_F(Unflocced), %	3.5	17.2	7.7
Initial Solids Content, S_i=3%			
S_F(Flocced), %	6.6	13.4	8.0
S_F(Unflocced), %	6.2	15.8	8.4
Initial Solids Content, S_i=8%			
S_F(Flocced), %	8.4	16.2	10.1
S_F(Unflocced), %	9.0	16.2	11.4

Where: S_F(unflocced) for S_i of 1% and 8% were taken from the Phase I clay tests (Volume 1, Table 3-1) and S_F(unflocced) for S_i of 3% was taken from the Phase II clay tests.

As shown, the test results indicate that as with clay and sand-clay mixes, a slurry prepared at a lower initial solids content and then flocced at the "optimum" flocculant loading rate generally will not attain as high a settled solids content as a flocced slurry prepared at a higher initial solids content. Further, the test results also show that the relatively low to medium plasticity phosphatic clays (i.e., CF and USSAC, respectively) display slightly lower "final" settled solids contents after flocculation than unflocced clay at all initial solids contents. The highly plastic Agrico phosphatic clay conversely displays slightly higher "final" settled solids contents after flocculation.

3.5.2 Laboratory Settling Rate

The initial settling rate, Q_o, achieved by each flocced clay and maximum settling rate, Q_1, achieved by each unflocced clay at initial solids contents of 1%, 3% and 8% are summarized below and in Figure 3-11.

Sample	S_i=1%		S_i=3%		S_i=8%	
	Q_o (cm/hr)	Q_1 (cm/hr)	Q_o (cm/hr)	Q_1 (cm/hr)	Q_o (cm/hr)	Q_1 (cm/hr)
Agrico-Saddle Creek	1944	0.71	792	0.11	1.2	0.03
CF Mining-Hardee	2778	53	3222	5.5	0.6	1.2
USSAC-Rockland	2052	14	348	0.32	0.36	0.17

Where: Q_1 for S_i of 1% and 8% were taken from the Phase I clay tests (Volume 1, Table 3-2) and Q_1 for S_i of 3% was taken from the Phase II clay tests.

The test results indicate that flocced clays as with unflocced clays exhibit an initial settling rate which generally decreases with increasing initial solids content. Further, the results show that the addition of flocculant results in significant increases in the settling rate (on the order of two to four orders of magnitude) for clays at initial solids contents of 1% and 3%. These clays also exhibited readily visible floc formation. For an initial clay solids content of 8%, however, no floc formation was visibly observed and flocculation accordingly was found to have essentially no effect on the settling rate of the relatively medium to low plasticity USSAC and CF phosphatic clays, and only a small effect on the highly plastic Agrico phosphatic clay.

3.6 Effect of Mixing During and After Flocculation on Settling Behavior and "Final" Settled Solids Content

During flocculation sufficient mixing must be used to disperse the flocculant within the clay suspension to allow the formation of clay flocs. Too little mixing does not promote floe formation and excessive mixing reduces floc size. Hence, an "optimum" mixing exists which produces the largest flocs and greatest improvement in settling behavior.

3.6.1 Mixing During Flocculation

The effect of mixing during flocculation on the settling behavior and "final" settled solids content of phosphatic clays was investigated for the CF clay at various flocculant loading rates and the USSAC and Agrico clays at one selected flocculant loading rate. Results from the settling tests are summarized below and in Figure 3-12.

	Sample		
Parameter	Agrico Saddle Creek	CF Mining Hardee	USSAC Rockland
Flocculant (lb/ton of clay)	1.2	0.6	1.2
Optimum Mixing			
Strokes	12	6	6
Time (sec)	15	10	10
S_F (%)	6.2	13.4	8.0
Q_o (cm/hour)	1.8	3660	348
Excessive Mixing			
Strokes	25	25	25
Time (sec)	120	120	120
S_F (%)	5.9	13.6	7.9
Q_o (cm/hour)	0.15	15.8	1.1

The "optimum" mixing consisted of six strokes in about 10 seconds for the relatively low to medium plasticity CF and USSAC clays and 12 strokes in about

15 seconds for the highly plastic Agrico clay. The mixing was performed with a perforated plunger type stirrer and "optimum" mixing was identified visually by the resulting floc size in the suspension. As shown, excessive mixing was found, as expected, to reduce floc size by breaking formed flocs which significantly reduces the initial settling rate. Little effect, however, occurred on the “final” settled solids content.

3.6.2 Mixing After Flocculation

The effect of mixing after flocculation on the settling behavior and "final" settled solids content was determined for each clay at 3% initial solids content flocced at the "optimum" flocculant loading rate. The clays were initially flocced and allowed to settle. Subsequently, the settled clay was remixed to the same initial solids content and allowed to again settle. The remixing was also repeated a second time. Results from these settling tests are summarized below and in Figure 3-13. Height of interface and solids content versus log time for each clay are also presented in Appendix E, Figures E-l, E-2 and E-3.

Sample	Initial Flocculation		First Remixing		Second Remixing	
	Q_o (cm/min)	S_F (%)	Q_o (cm/min)	S_F (%)	Q_o (cm/min)	S_F (%)
Agrico-Saddle Creek	16.4	6.8	0.01	6.8	0.01	6.3
CF Mining-Hardee	46.4	12.8	0.4	15.0	0 . 1	13 9
USSAC-Rockland	4.1	8.4	0.02	8.5	0.01	8.1

After each remixing, flocs were visible in the suspensions, but to progressively lesser degrees with additional mixing than during initial flocculation. This observation is evidenced by the significant and progressive decrease in initial settling rate with increased mixing (Figure 3-13). Remixing, however, had relatively little effect on the "final" settled solids content.

3.7 Variable Initial Height Settling Tests and Extrapolation of Laboratory Settling Behavior to Field Conditions

Variable initial height settling tests were performed on each of the three selected clays at initial solids contents of 3% and 8% using the "optimum" flocculant loading rate. Initial heights of 6, 12, 18 and 24 cm were used. Additionally, one settling test was performed with an initial height in the range of 40 to 55 cm for each clay at an initial solids content of 3%.

The results of the variable initial height settling tests were evaluated with the Michaels and Bolger (1962) methodology to allow extrapolation of the laboratory settling test behavior in a "limited" size container to the field condition of an "infinite" size container. The evaluations were performed using the interpretation methodology previously presented in Volume 3, Section 2.4. Solids content and height of interface versus time plots for each settling test are presented in Appendix F, Figures F-l through F-9.

3.7.1 Relationship Between Laboratory Initial Settling Rate and Initial Solids Content

The settling behavior of phosphatic clays at an initial solids content of 3% was previously shown in Volume 3 to be consistent with the Michaels and Bolger (1962) model for clay slurries of intermediate concentration. At intermediate concentrations, settling occurs as a coherent network of clusters of flocs or aggregates. When the phosphatic clays are artificially flocced, however, the aggregates do not form a coherent network, but rather behave as a dilute suspension and settle as roughly spherical individual units. Michaels and Bolger (1962) show that the group settling rate for uniform, spherical particles (or aggregates) can be modelled by the expression:

$$Q_o = ((\rho-\rho_w)\bar{d}_A{}^2)(1-C_{AK}\phi_K)^{4.65}/(18(\mu_w/g)C_{AK}) \qquad (2)$$

where as previously defined above and in Volume 3, Section 2.4: Q_o is the initial settling rate; ρ is the specific gravity of clay solids; ρ_w is the supernatant specific gravity; $\bar{d}_A$ is the average equivalent aggregate diameter; C_{AK} is the ratio ϕ_A/ϕ_K; ϕ_A is the aggregate volume concentration; ϕ_K is clay volume concentration; μ_w is the absolute viscosity of the supernatant; and g is gravitational acceleration. Further, with $\bar{d}_A$ in units of cm and Stoke's settling velocity, V_{SA}, for a single aggregate in units of cm/min, the relationship between $\bar{d}_A$ and V_{SA} can be expressed by the equation:

$$\bar{d}_A = (1/604)((V_{SA}C_{AK})/(\rho-1))^{0.5} \qquad (3)$$

Combining Equations 2 and 3 and substituting values for ρ, ρ_w, μ_w and g yields the following linear relationship between Q_o and ϕ_K in terms of V_{SA}:

$$Q_o{}^{1/4.65} = V_{SA}{}^{1/4.65} - C_{AK}V_{SA}{}^{1/4.65}(\phi_K) \qquad (4)$$

Physically, Equation 4 shows that as the solids content approaches zero, Q_o approaches V_{SA} and that as the solids content (or ϕ_K)* increases Q_o decreases.

The relationship between $Q_o{}^{1/4.65}$ and ϕ_K for the three selected phosphatic clays at the "optimum" flocculant loading rate is presented in Figure 3-14 based on settling tests with initial solids contents of 1%, 3% and 8%. Relevant parameters determined for each clay using Equations 3 and 4 are presented below:

Sample	V_{SA} (cm/min)	C_{AK}	$\bar{d}_A$ (cm)
Agrico-Saddle Creek	97.7	35.33	0.073
CF Mining-Hardee	329.8	33.09	0.129
USSAC-Rockland	55.9	34.72	0.055

*Solids content and clay volume concentration are related by the expression: $\phi_K = S/(S+(1-S)\rho)$.

As shown, the $Q_o^{1/4.65}$ versus ϕ_K relationship for each clay is approximately linear. Accordingly, it appears that the Michaels and Bolger (1962) methodology for dilute suspensions is applicable to flocculated phosphatic clays. Linear regression analyses of the data yield Stoke's settling velocities ranging from 55.9 cm/min to 329.8 cm/min. The average equivalent aggregate diameters are relatively similar ranging from 0.055 to 0.078 cm and averaging about 0.07 cm.

3.7.2 Field Settling Rate

For a given initial solids content, S_i, or clay volume concentration, ϕ_K, and several settling tests with varying initial sample heights, the laboratory initial settling rate, Q_o, can be extrapolated to indicate the field initial settling rate, Q_o', to be expected.

The maximum field settling rate was determined via the relationship between the measured initial settling rate, Q_o, and the inverse of the initial sample height, $1/Z_o$. The field initial settling rate was then interpreted to be the settling rate determined from the relationship for a $1/Z_o$ value of 0 (i.e., an infinite sample height). Figure 3-15 illustrates the Q_o versus $1/Z_o$ relationships for each clay at 3% initial solids content and "optimum" flocculant loading rate. The extrapolated field initial settling rates are shown at $1/Z_o=0$ (ordinate intercept) and are summarized below:

Sample	Field Initial Settling Rate, Q_o' (cm/min)	Laboratory Initial Settling Rate for Z_o=24cm, Q_o (cm/min)	Q_o'/Q_o
Agrico-Saddle Creek	28.5	14.0	2.0
CF Mining-Hardee	71.8	46.4	1.5
USSAC-Rockland	42.2	15.0	2.8

As shown, at 3% initial solids content the field initial settling rate is projected to be 1.5 to 2.8 (with an average of 2.1) times faster than the laboratory initial settling rate determined on samples with an initial height of 24 cm. This result can be used as a general guideline to correct laboratory initial settling rates on flocced clay samples when the effect of different initial sample heights is not known. This relationship, however, is only applicable strictly to NALCO 7877 flocculant added to the clay in accordance with the described test methods.

3.7.3 Floc Volume Concentration of Flocculated Suspensions

Physically, the floc volume concentration, ϕ_F, is the ratio of the volume of the flocs to the total volume of the clay suspension. Flocs are composed of clusters of clay particles plus inter-floc water.

The floc volume concentration was determined as outlined by Michaels and Bolger (1962) from the slope of the linear portion of the curve obtained by constructing a plot of the height of the clays solids within the suspension, $Z_o\phi_K$, versus the "final" settled height, Z_F, of the suspension. Based on the Michaels and Bolger (1962) methodology, the settled clay consists of a lower uniform density (or uniform solids content) region plus an upper nonuniform density zone. The ordinate intercept of the $Z_o\phi_K$ versus Z_F curve, therefore, is the constant thickness of the upper nonuniform lower density zone. The slope of the curve is the constant relating the "final" settled height, Z_F, to the height of the clay solids, $Z_o\phi_K$.

Plots of $Z_o\phi_K$ versus Z_F obtained for each clay at initial solids contents of 3% and 8% using the "optimum" flocculant loading rate are presented in Figure 3-16. The least squares linear regression equations for the fitted lines are presented in Table 3-2 and compared to parameters previously established for unflocced clays (Volume 3, Section 3.3.4). For the flocced clays the parameters are shown based on the initial solids content and corresponding clay volume concentration both prior to and after adding flocculant. Note that in Figure 3-16 the relationships are shown for the clay volume concentration without adjustments for the flocculant added to the suspension.

The determination of the floc volume concentration is based on the assumption that the clay flocs settle in the lower uniform density zone to form a "final" settled structure of random, closely-packed arrays of spheres having a solid volume fraction of 0.62. The "final" settled height of a clay suspension, therefore, can be written as:

$$Z_F = b+(H_F/0.62) \quad (5)$$

where: Z_F is the "final" settled height; H_F is the height of clay flocs; and b is the thickness of the surficial nonuniform low density settled zone where the clay flocs are not closely packed.

By definition, the floc volume concentration, ϕ_F, is the ratio H_F/Z_o. Equation 5, therefore, can be rewritten as:

$$Z_F = b+(Z_o\phi_F/0.62) \quad (6)$$

From Figure 3-16, the expression for Z_F is of the form:

$$Z_F = b+\alpha(Z_o\phi_K) \quad (7)$$

where α and b are least squares estimators of the slope and intercept, respectively. Combining Equations 6 and 7 yields the following expression for ϕ_F:

$$\phi_F = 0.62\,\alpha\phi_K \quad (8)$$

The floc volume concentrations determined from Equation 8 are presented in Table 3-2 and graphically summarized in Figure 3-17 as a function of clay volume concentration, which is directly related to initial solids content. The floc volume concentrations previously established for the unflocced clay are also included for comparison. As it turns out, the floc volume concentrations of the flocced and unflocced clays are not significantly different!

3.7.4 "Final" Settled Height and Field Solids Content

Using the equations summarized in Table 3-2, the "final" settled height for any initial height at initial solids contents of 3% and 8% can be obtained. As shown in Figure 3-16, the "final" settled heights can vary significantly between clays with the same initial sample height.

Based on Equation 7 presented above, it can be shown that the "final" average solids content, S_F, for a given initial height can be calculated from the following:

$$S_F = \rho/(\rho-1+((b+\alpha Z_o\phi_K)/Z_o\phi_K)) \qquad (9)$$

where: ρ is the specific gravity of clay solids; α is the slope of Z_F versus $Z_o\phi_K$ curve; and b is the ordinate intercept of the Z_F versus $Z_o\phi_K$ curve.

As shown in Figure 3-18, for relatively small values of initial height (i.e., about 20 to 30 cm) in comparison to the b value, the average "final" settled solids content increases slightly with increasing initial sample height. For large values of initial height in comparison to the b value, the average "final" settled solids content remains essentially independent of initial height.

3.8 Void Ratio Versus Effective Stress Relationships at Low Effective Stresses

The "final" settling test heights and solids contents were used to estimate the solids content (or void ratio) versus effective stress compressibility curves at the very low effective stresses that result from limited self-weight consolidation.* The effective vertical consolidation stress, $\bar{\sigma}_{vc}$, and void ratio, e, were determined from settling tests on the same flocculated clay with initial heights of 6.0, 12.0, 18.0 and 24.0 cm. The effective stress versus void ratio relationship was developed for the lowermost initial 6.0 cm clay zone for each test. This was accomplished by first determining Z_F, $\bar{\sigma}_{vc}$ and e for the 6.0 cm high test sample. The final height, Z_F, of the 6.0 cm high sample was then subtracted from the final height of the 12.0 cm high sample to determine the Z_F and e of the lower 6.0 cm zone of the 12.0 cm high sample. This iterative approach was continued for the 18.0 and 24.0 cm high samples. The advantage of this approach over the simpler technique of taking one average $\bar{\sigma}_{vc}$ and e for each test is that it accounts for variations in solids content with depth.

The void ratio versus effective stress relationship developed for each clay at the "optimum" flocculant loading rate from the variable initial height settling tests using this approach, and from the constant height settling tests using the simpler

*Solids content, S, and void ratio, e, are related by the expression: $e = (\rho(1-S)/S)$, where ρ is the specific gravity of clay solids.

average approach are shown in Figure 3-19. Void ratio versus effective stress data previously established for unflocced clay (Volume 3, Section 3.4) are also presented in Figure 3-19 for comparison. Tables B-1, B-2 and B-3 in Appendix B summarize relevant data used to determine the void ratio versus effective stress relationships.

Least squares power function regressions of the form $e_f = \alpha \bar{\sigma}_{vc}^{\beta}$ with $\bar{\sigma}_{vc}$ in units of lb/ft^2 are shown on Figure 3-19 and summarized below for flocced and unflocced clay at extremely low effective stresses.

	$e_F = \alpha\ \bar{\sigma}_{vc}{}^{\beta}$			
	Flocced		Unflocced	
Sample	α	β	α	β
Agrico-Saddle Creek	30.84	-0.238	30.79	-0.359
CF Mining-Hardee	14.37	-0.142	12.22	-0.075
USSAC-Rockland	24.81	-0.183	25.47	-0.244

As shown, the selected clays exhibit a wide range of behavior with the Agrico clay exhibiting the highest "final" void ratio at a given effective stress and the CF clay exhibiting the lowest "final" void ratio at a given effective stress.

3.9 **Summary and Practical Implications**

Settling tests performed on flocculated clays indicated a wide range of settling characteristics. The sedimentation behavior of the flocculated phosphatic clays was evaluated to determine the effect of flocculant loading rate on settling behavior and "final" settled solids content, the effect of initial solids content, the effect of mixing during and after flocculation, and the applicability of the Michaels and Bolger (1962) methodology. The significant practical findings determined from the investigation are summarized below. Note, that these findings are applicable strictly for NALCO 7877 flocculant added to the clay in one increment in accordance with the described laboratory test methods and procedures. Different findings may result for other flocculants and flocculant methods and the relative performance of the various clays with other flocculants may be substantially different. Nevertheless, the findings can be used as a guide for evaluating the potential effects of flocculation on sedimentation behavior.

Based on settling tests with an initial solids content of 3% and initial height of 24 cm, the following behavioral characteristics were observed:

- Flocculation was found, as expected, to significantly increase the initial settling rates of phosphatic clays by two to three orders of magnitude. Clays of higher plasticity, however, required a higher flocculant loading rate to achieve the same relative increase in initial settling rate.

- A maximum initial settling rate is attained for a given clay at an optimum flocculant loading rate beyond which the addition of more flocculant is detrimental and produces lower initial settling rates.

- Clays which settle to relatively low solids contents naturally also settle to relatively low solids contents with flocculation. Low to medium plasticity phosphatic clays were actually found to display a modest to slight decrease in “final” settled solids content when flocced, with the magnitude of the decrease increasing with increasing flocculant loading rate. Conversely, high plasticity phosphatic clays were found to display a very slight increase in "final" settled solids when flocced. Hence, the only benefit of flocculation is to improve the initial settling rate.

- Excessive or too little mixing during flocculation and remixing after flocculation were found to adversely affect the initial settling rates due to breaking-up of the flocs. Little effect, however, was observed on the "final" settled solids content.

Additional tests performed at initial solids contents of 1% and 8% using the “optimum” flocculant loading rate (determined for an initial solids content of 3%), indicated that the initial settling rate was significantly increased for clay with an initial solids content of 1% but only slightly affected for clay with an initial solids content of 8%.

Based on settling tests with initial solids contents of 3% and 8%, and variable heights of 6 to 50 cm, the following characteristics were determined in accordance with the Michaels and Bolger (1962) methodology for extrapolating laboratory settling behavior to field conditions:

- The settling behavior of artificially flocced phosphatic clays is reasonably consistent with the Michaels and Bolger (1962) methodology. The methodology, therefore, is applicable for estimating the settling behavior of flocced phosphatic clays.

- At 3% initial solids content, the field initial settling rate for flocced clays may be up to two times faster than inferred from laboratory initial settling rates. Laboratory settling rates, therefore, should be increased when predicting field settling rates to account for the laboratory effects of a limited size container.

- The "final" settled solids contents occurring in the field may be up to 1.2 times those inferred from laboratory "final" settled solids contents.

Table 3-1

SETTLING TEST RESULTS FOR PHOSPHATIC CLAYS AT 3% INITIAL SOLIDS CONTENT WITH VARIOUS FLOCCULANT LOADING RATES

Sample	Polymer Loading Rate (lb/ton of clay)	Initial Condition S_i (%)	Initial Condition Z_o (cm)	Initial Condition S_{if} (%)	Initial Condition Z_{of} (cm)	Initial Settling Rate, Q_o (cm/min)	t = 100 minutes S (%)	t = 100 minutes Q_s (cm/min)	Final Condition S_F (%)	Final Condition Z_F (cm)
Agrico Saddle Creek	0.0	3.00	24.0	3.00	24.0	0.002*	3.00	0.005	6.18	11.3
	1.2	2.95	22.6	2.79	23.9	0.03	2.90	0.004	6.23	10.9
	1.8	2.95	21.9	2.71	23.9	1.5	4.65	0.098	6.32	10.0
	2.4	2.95	21.3	2.64	23.6	10	5.80	0.126	6.60	9.3
	3.6	2.95	20.3	2.51	23.7	7.4	5.10	0.127	6.19	9.2
CF Mining Hardee	0.0	3.00	24.0	3.00	24.0	0.09*	4.30	0.061	15.80	4.2
	0.3	2.99	23.7	2.95	24.2	32	9.40	0.169	13.05	5.1
	0.6	2.99	23.3	2.90	24.1	61	10.10	0.173	13.45	4.9
	1.2	2.99	22.6	2.82	24.0	100	11.00	0.181	12.96	4.9
	2.4	2.99	21.3	2.67	23.9	89	10.70	0.182	12.05	5.0
USSAC Rockland	0.0	3.00	24.0	3.00	24.0	0.005*	3.10	0.005	8.37	8.3
	0.6	3.00	23.3	2.91	24.2	0.05	3.25	0.038	7.58	8.6
	1.2	3.00	22.6	2.83	24.0	5.8	5.90	0.129	7.99	8.2
	2.4	3.00	21.3	2.68	23.8	15	6.05	0.135	7.64	8.1
	3.6	3.00	20.3	2.55	24.1	4.7	5.95	0.141	6.78	8.7

Nomenclature: S_i = Initial unflocced clay solids content; Z_o = Initial height of unflocced clay suspension; S_{if} = Initial flocced clay solids content; Z_{of} = Initial height of flocced clay suspension; Q_o = Initial settling rate; S = Settled solids content at 100 minutes; Q_s = Secant settling rate at 100 minutes; t = Time; S_F = "Final" settled solids content; Z_F = "Final" settled height.

* Initial settling rate for unflocced clay taken as maximum settling rate, Q_1 (see Section 2, Table 2-3).

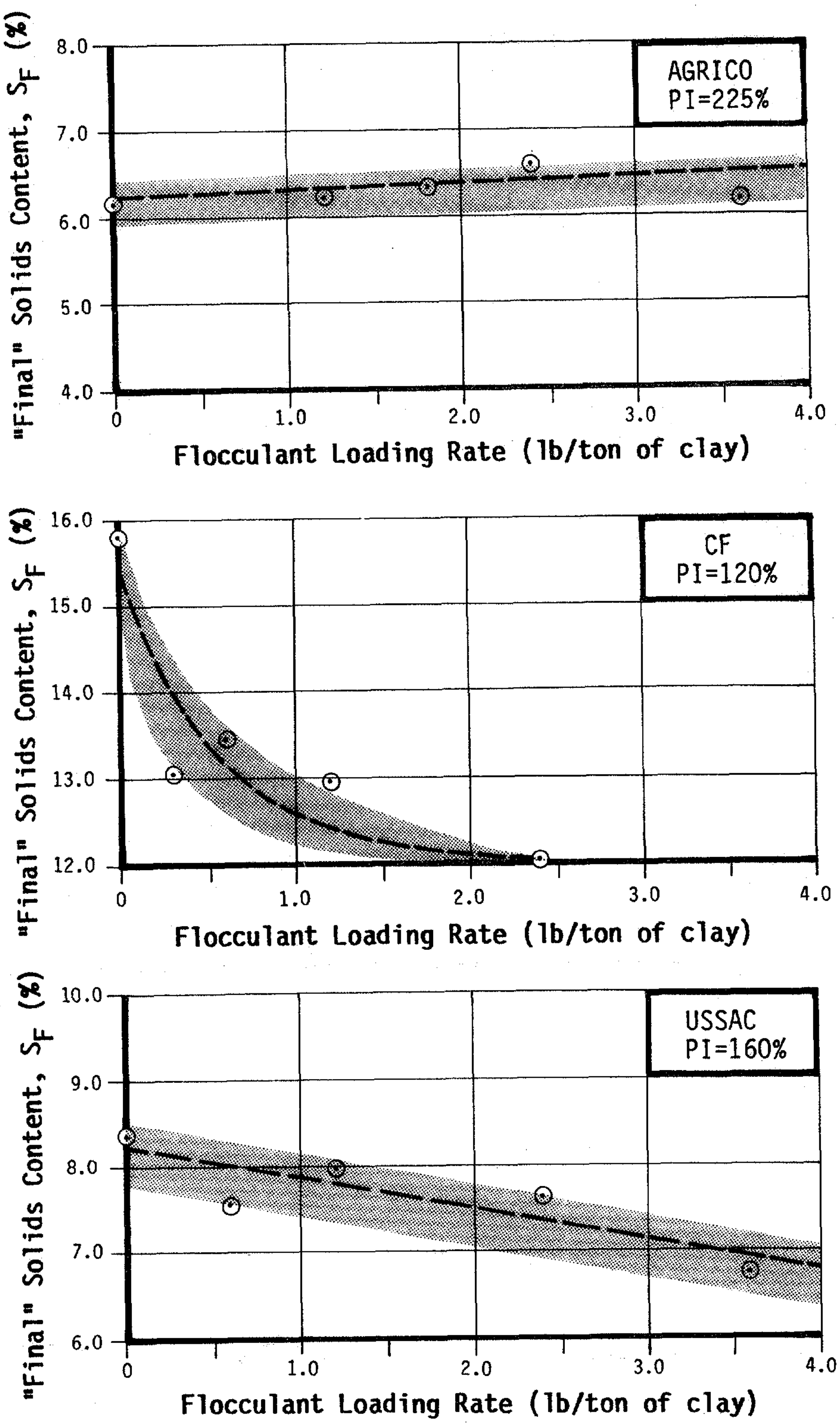
Table 3-2

COMPARISON OF FLOC VOLUME CONCENTRATION FOR UNFLOCCED PHOSPHATIC CLAYS AND PHOSPHATIC CLAYS AT OPTIMUM FLOCCULANT LOADING RATE

	$Z_F = b+\alpha(Z_o\phi_K)$						$Z_F = b+\alpha(Z_o\phi_K)$					
Sample	S_i (%)	ϕ_K	b	α	r	ϕ_F	S_i (%)	ϕ_K	b	α	r	ϕ_F
• Unflocced Clays												
Agrico-Saddle Creek	3.0	0.0110	0.90	45.91	0.999	0.313	8.0	0.0302	0.80	27.98	0.999	0.525
CF Mining-Hardee	3.0	0.0109	0.12	13.34	0.999	0.092	8.0	0.0300	0.26	13.33	0.999	0.250
USSAC-Rockland	3.0	0.0109	0.90	30.15	0.999	0.202	8.0	0.0300	0.94	22.53	1.000	0.418
• Flocced Clays												
Agrico-Saddle Creek	3.0*	0.0110	1.60	32.76	0.998	0.223	8.0*	0.0304	0.35	30.27	1.000	0.571
Agrico-Saddle Creek	2.75**	0.0100	1.60	32.10	0.998	0.201	6.21**	0.0233	0.34	30.55	1.000	0.441
CF Mining-Hardee	3.0*	0.0109	0.29	17.35	0.998	0.117	8.0*	0.0300	0.46	14.90	0.999	0.277
CF Mining-Hardee	2.89**	0.0105	0.28	17.58	0.998	0.114	7.46**	0.0278	0.46	15.01	0.999	0.259
USSAC-Rockland	3.0*	0.0110	1.18	25.22	0.996	0.174	8.0*	0.0305	0.79	24.35	1.000	0.461
USSAC-Rockland	2.83**	0.0104	1.24	24.96	0.996	0.161	6.98**	0.0264	0.78	24.47	1.000	0.400

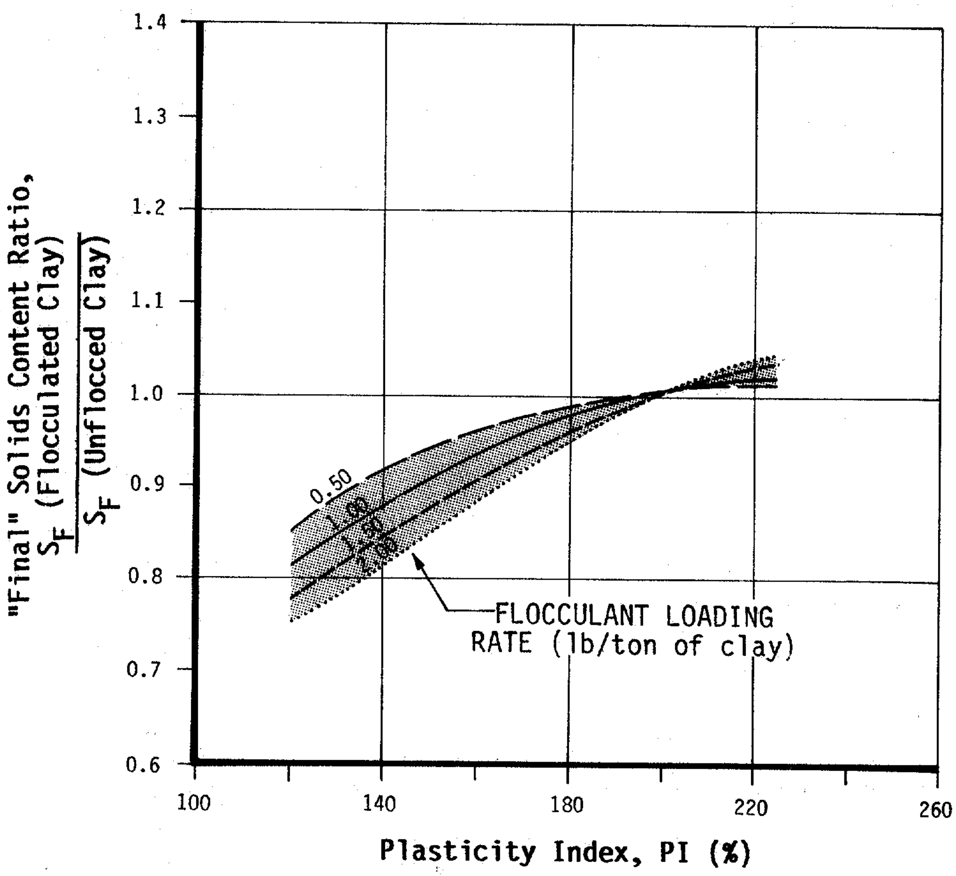
Nomenclature: S_i = Initial clay solids content; b and α = Least squares linear estimators of intercept and slope of $Z_o\phi_K$ and $Z_o f \phi_K$ versus Z_F; r = Correlation coefficient; ϕ_F = Floc volume concentration; ϕ_K = Clay volume concentration; Z_o = Initial height; Z_F = "Final" settled height.

*Initial solids content of clay prior to adding flocculant, S_i.
**Initial solids content of clay after adding flocculant, S_{if}.



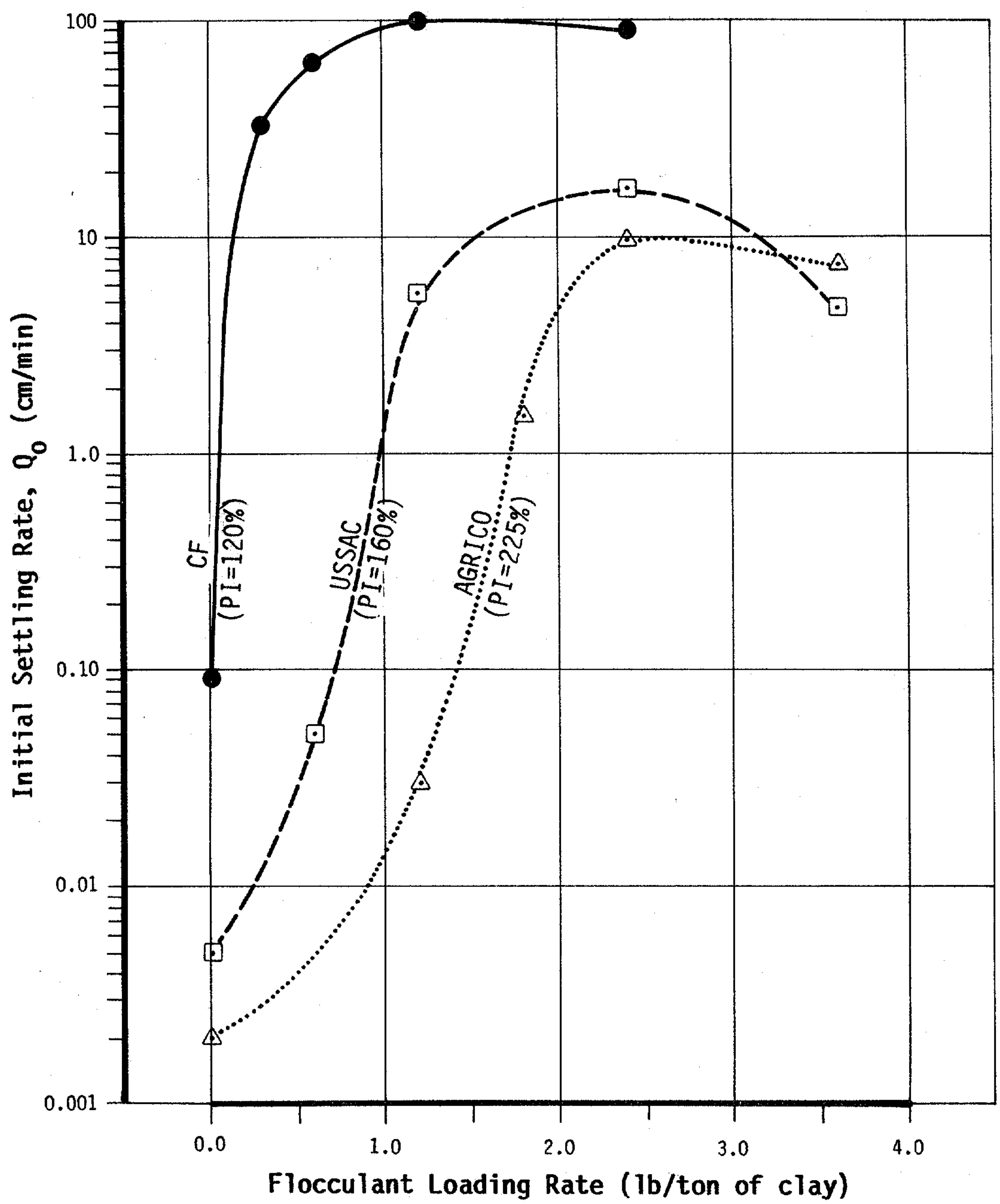
EFFECT OF FLOCCULANT LOADING RATE ON "FINAL" SOLIDS CONTENT FOR PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT

FIGURE 3-1



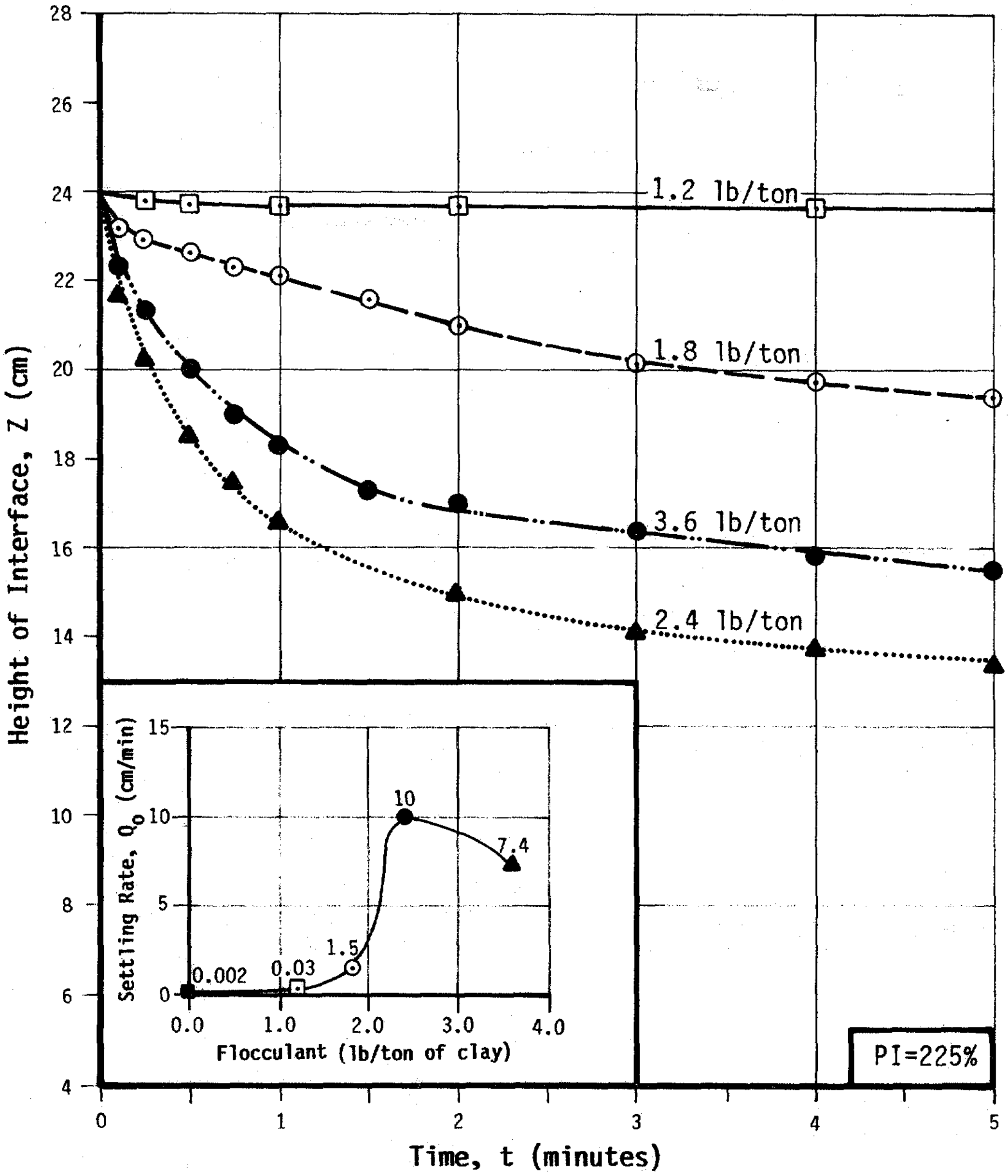
PLASTICITY INDEX VS. "FINAL" SOLIDS CONTENT RATIO FOR PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT

FIGURE 3-2



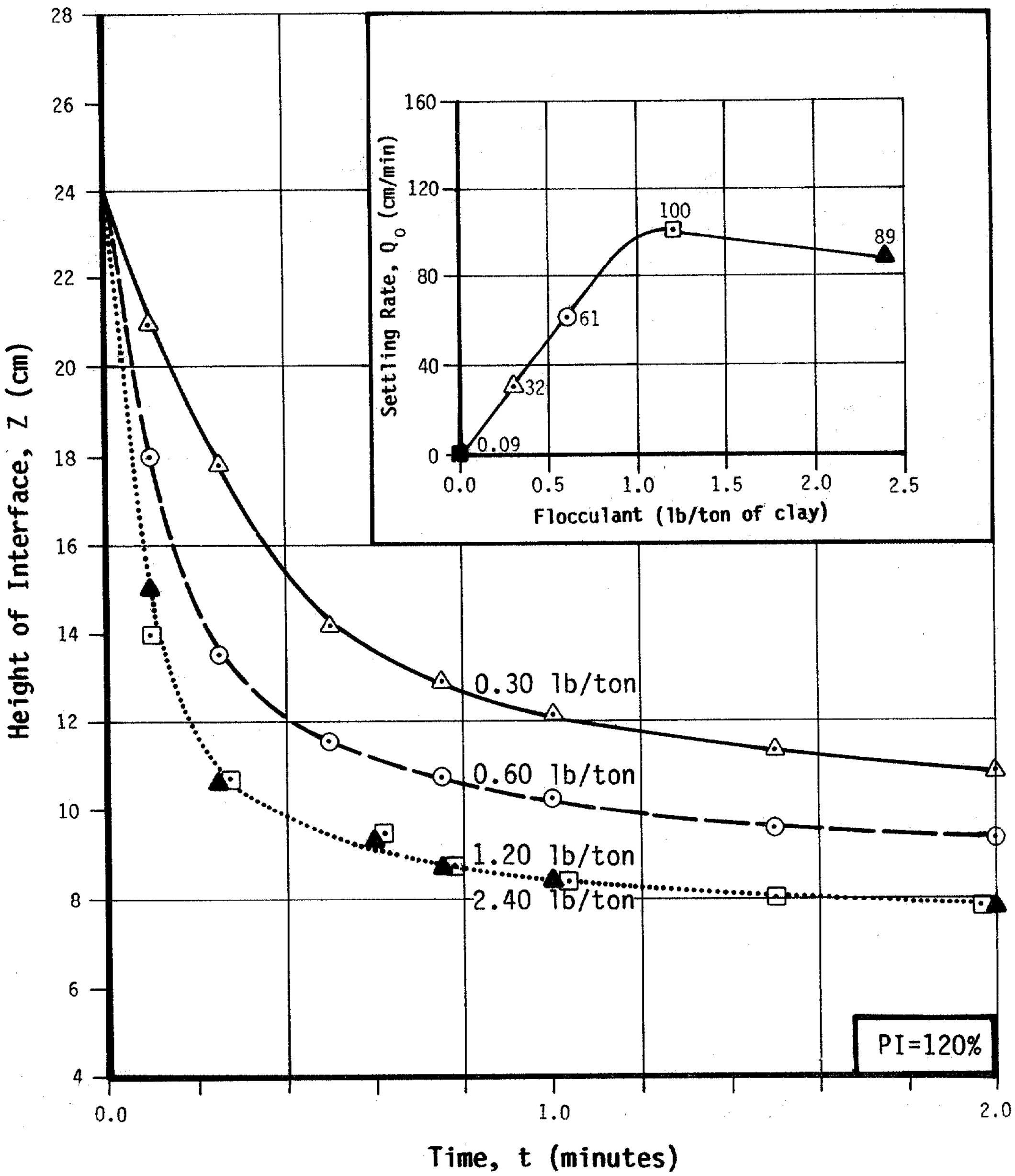
FLOCCULANT LOADING RATE VS. INITIAL SETTLING RATE FOR PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT

FIGURE 3-3



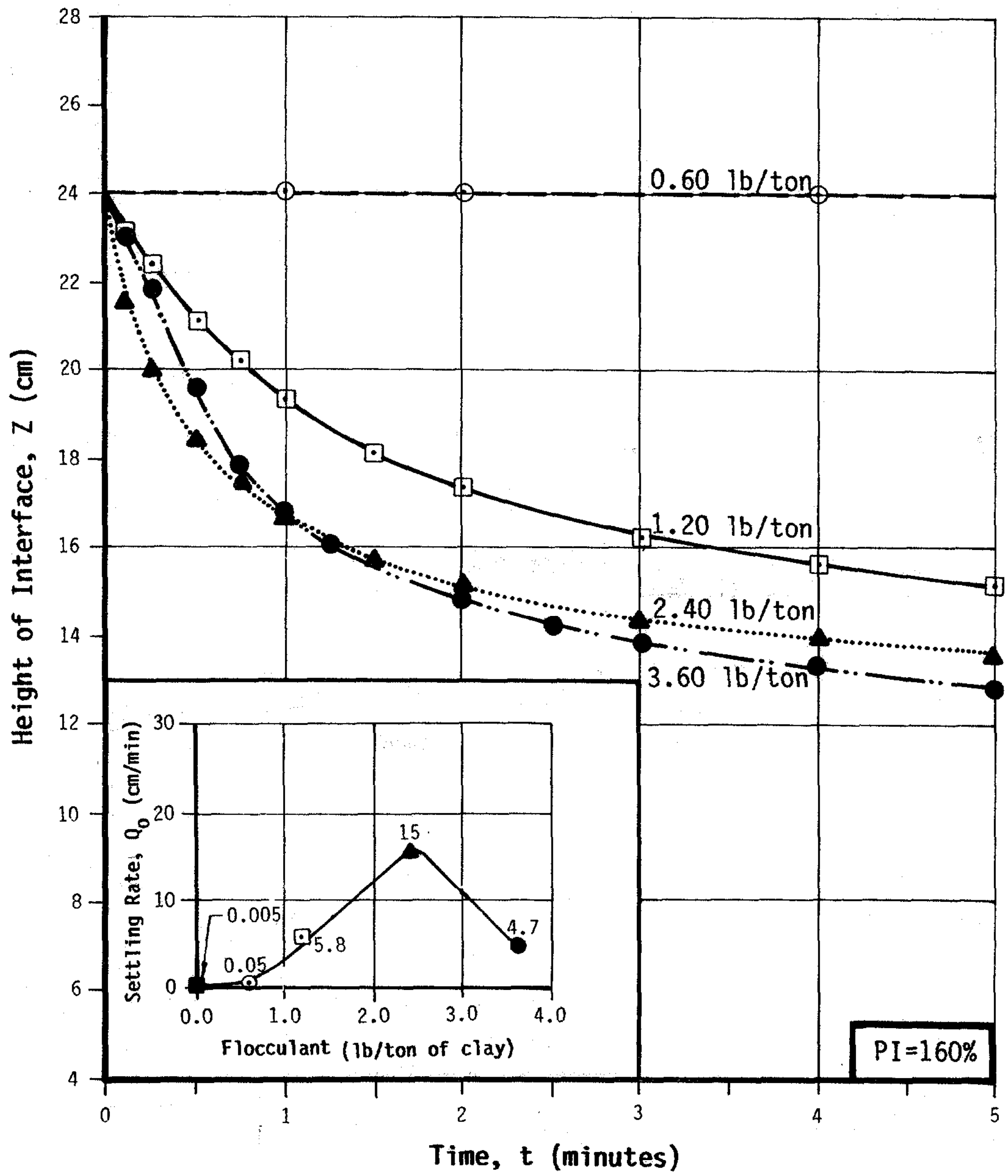
EFFECT OF FLOCCULANT LOADING RATE ON INITIAL SETTLING RATE OF AGRICO-SADDLE CREEK PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT

FIGURE 3-4



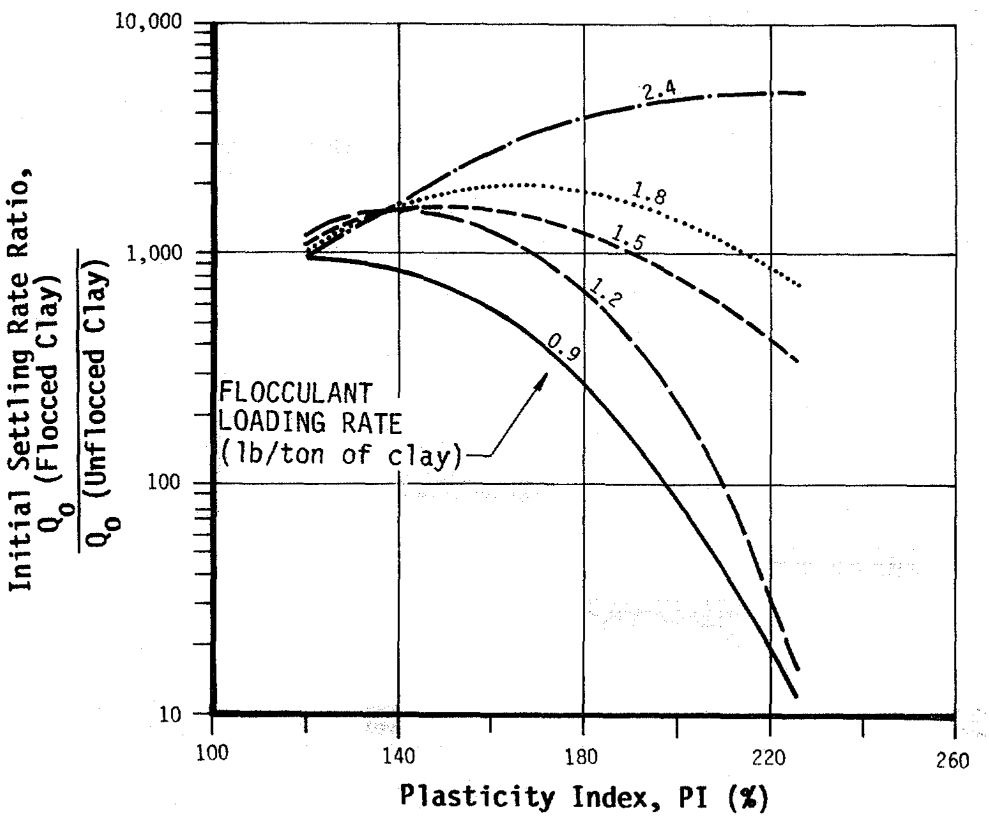
EFFECT OF FLOCCULANT LOADING RATE ON INITIAL SETTLING RATE OF CF MINING-HARDEE PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT

FIGURE 3-5



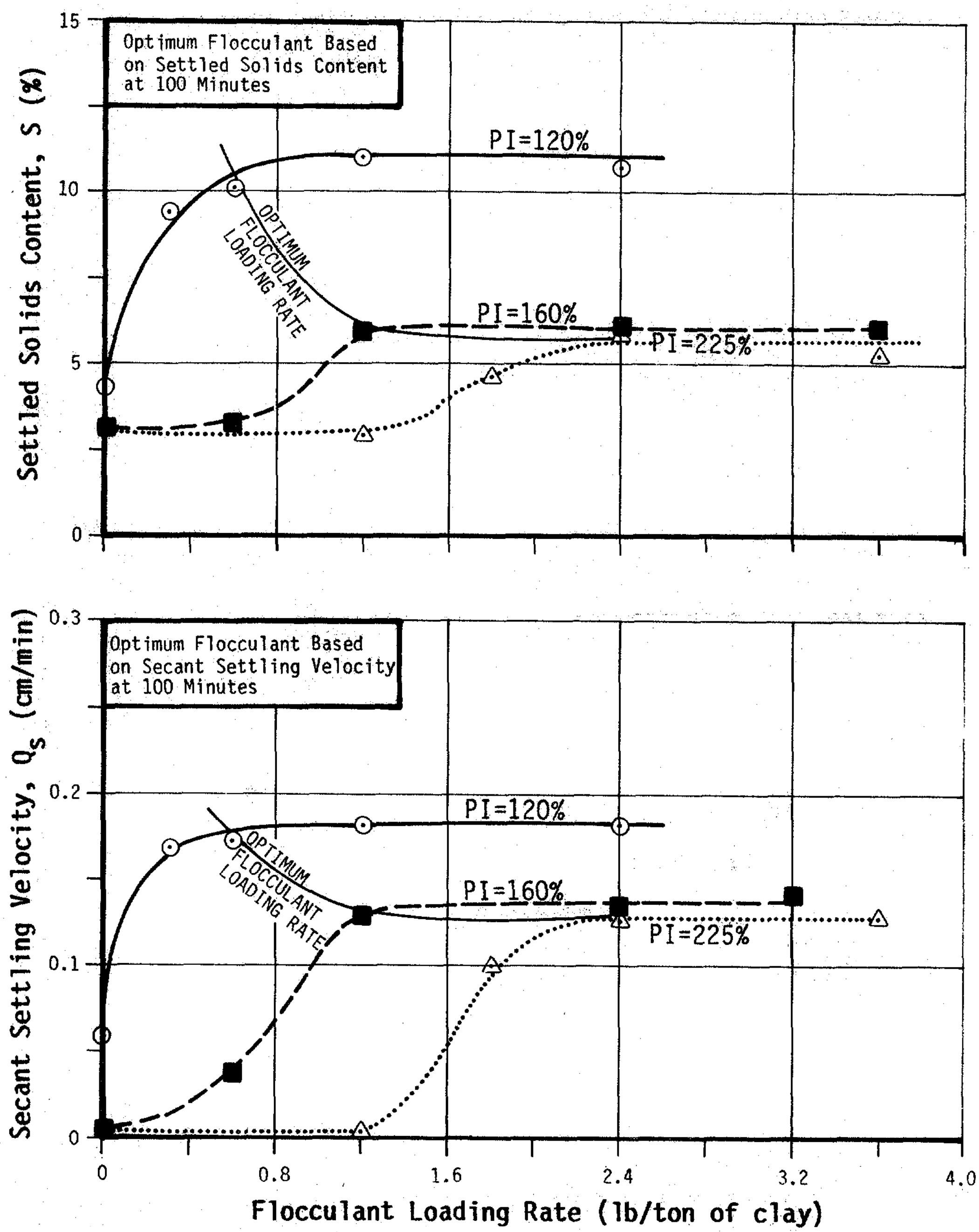
EFFECT OF FLOCCULANT LOADING RATE ON INITIAL SETTLING RATE OF USSAC-ROCKLAND PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT

FIGURE 3-6



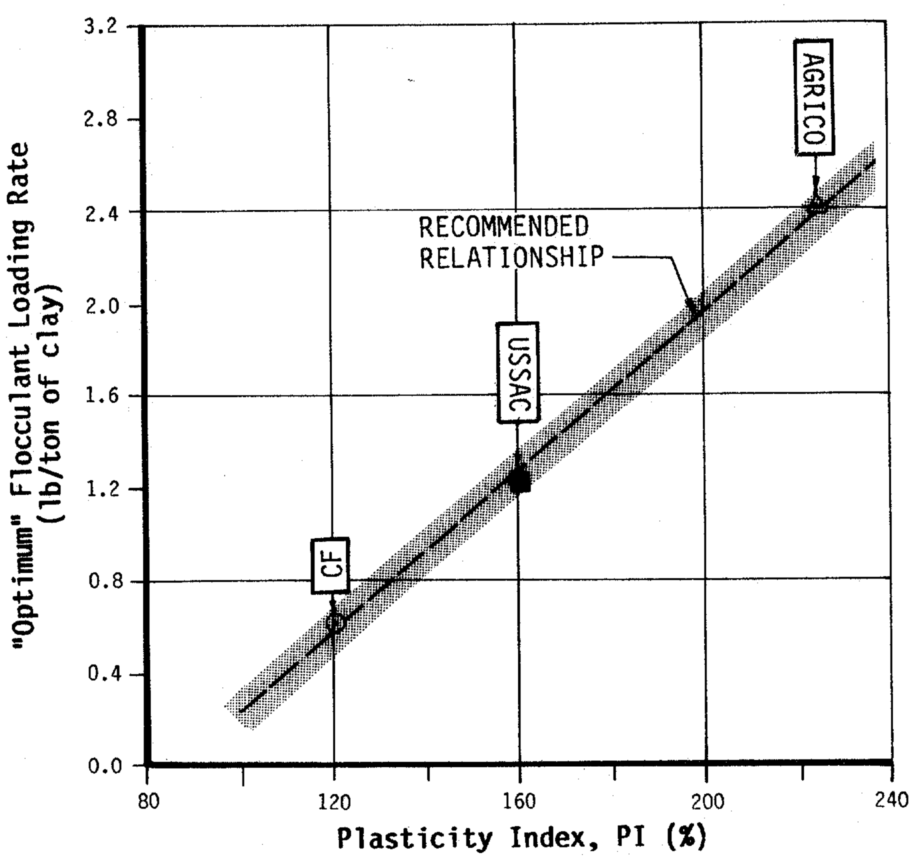
PLASTICITY INDEX VS. INITIAL SETTLING RATE RATIO FOR PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT

FIGURE 3-7



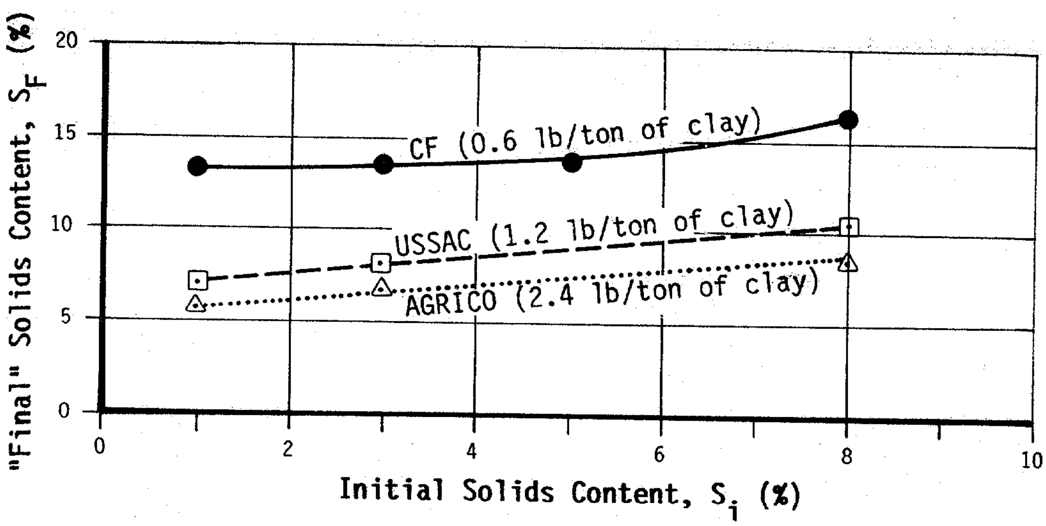
OPTIMUM FLOCCULANT LOADING RATE FOR PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT

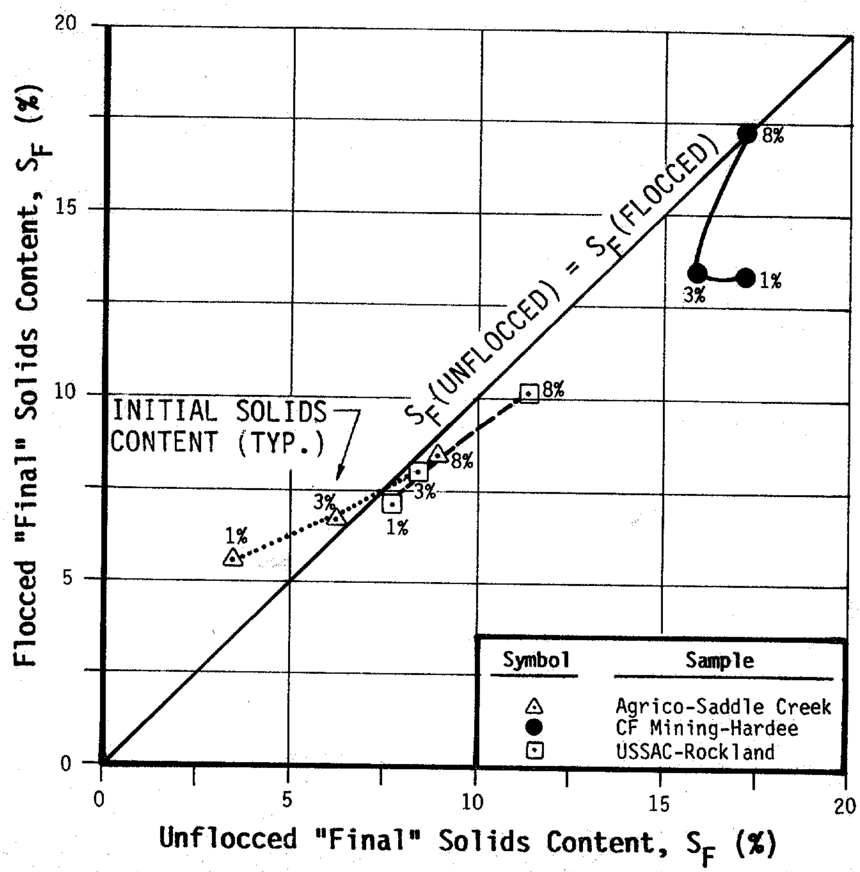
FIGURE 3-8



PLASTICITY INDEX VS. OPTIMUM FLOCCULANT LOADING RATE FOR NALCO 7877 FLOCCULANT FOR PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT

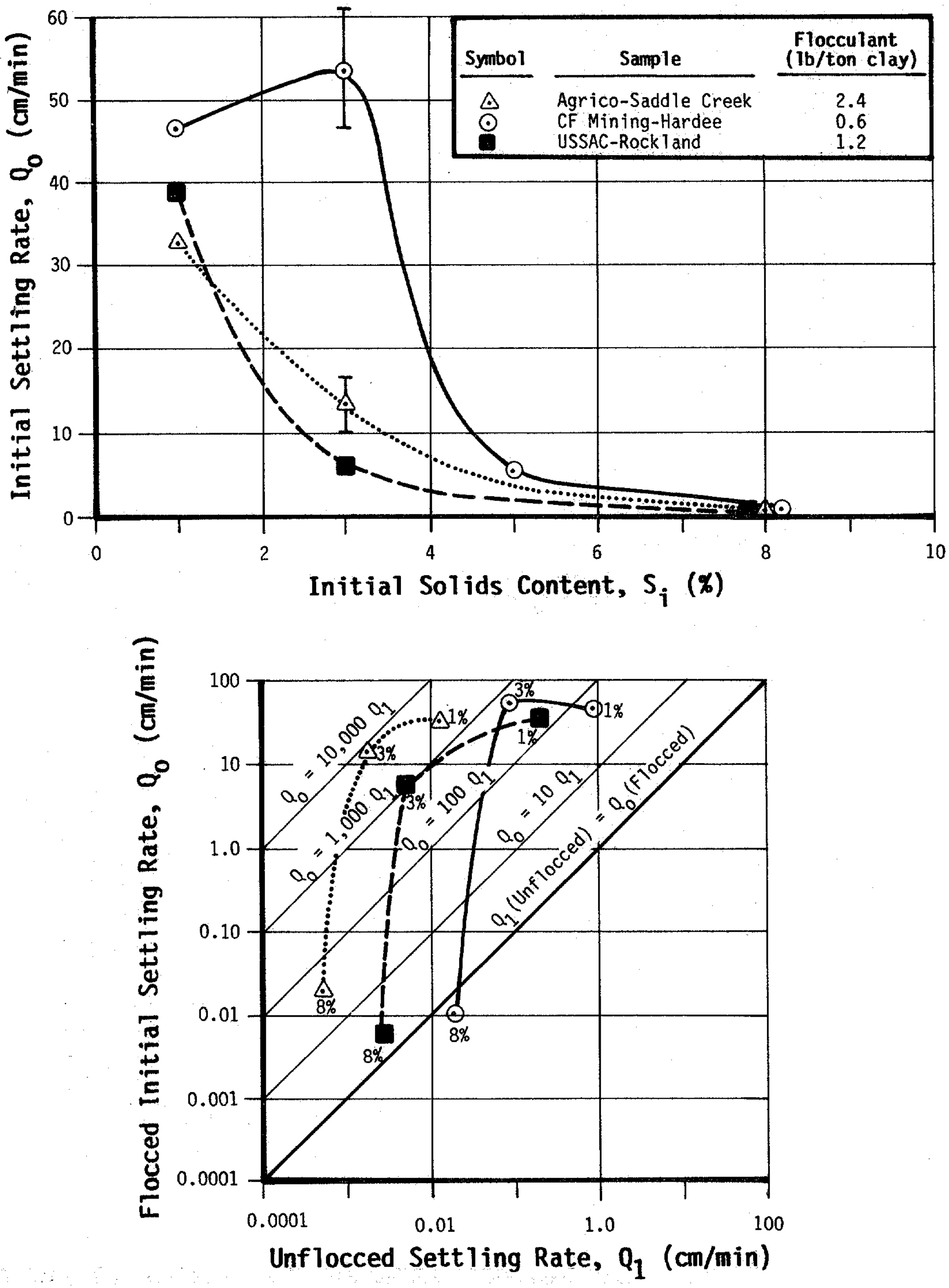
FIGURE 3-9





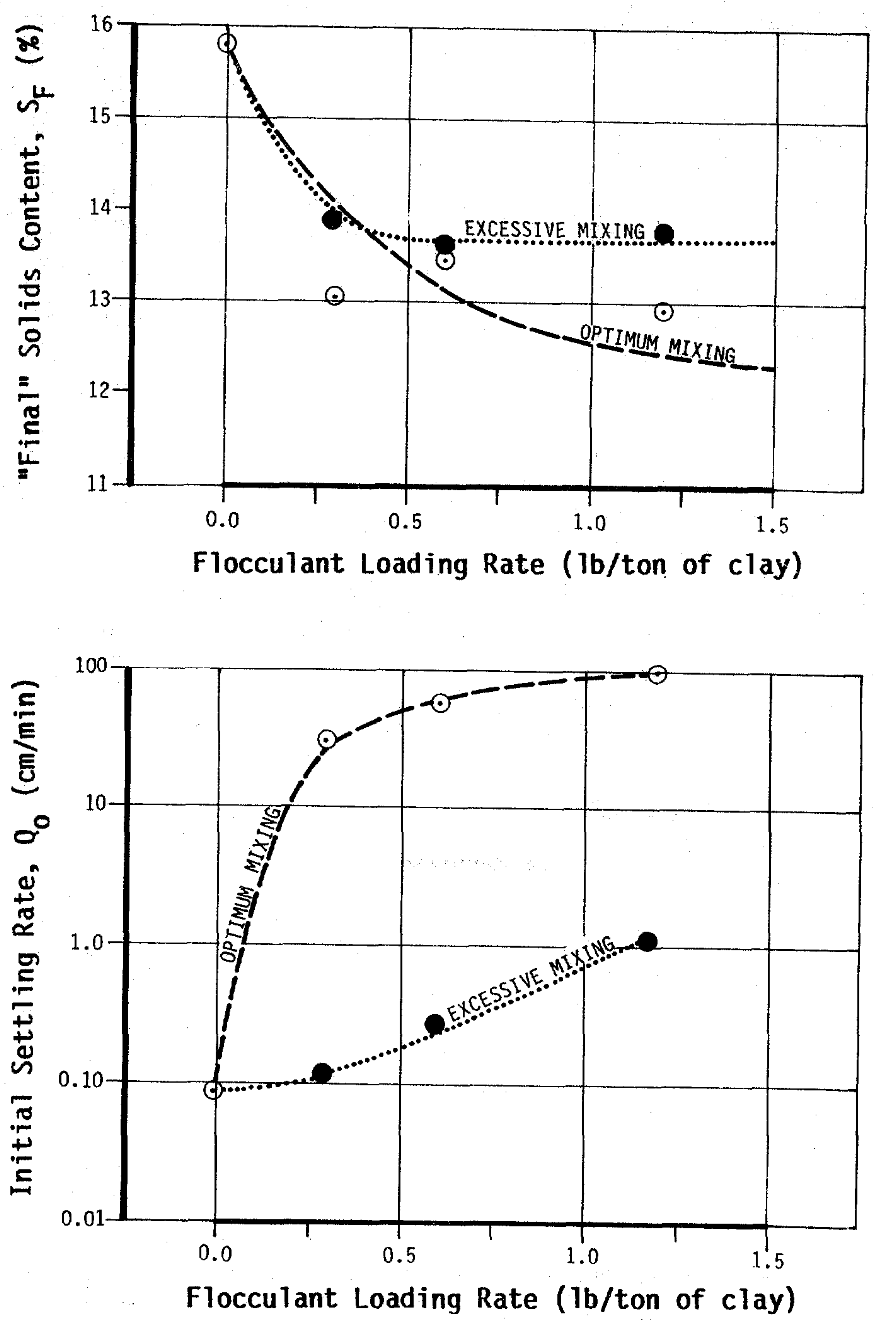
EFFECT OF INITIAL SOLIDS CONTENT ON "FINAL" SOLIDS CONTENT FOR PHOSPHATIC CLAY AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 3-10



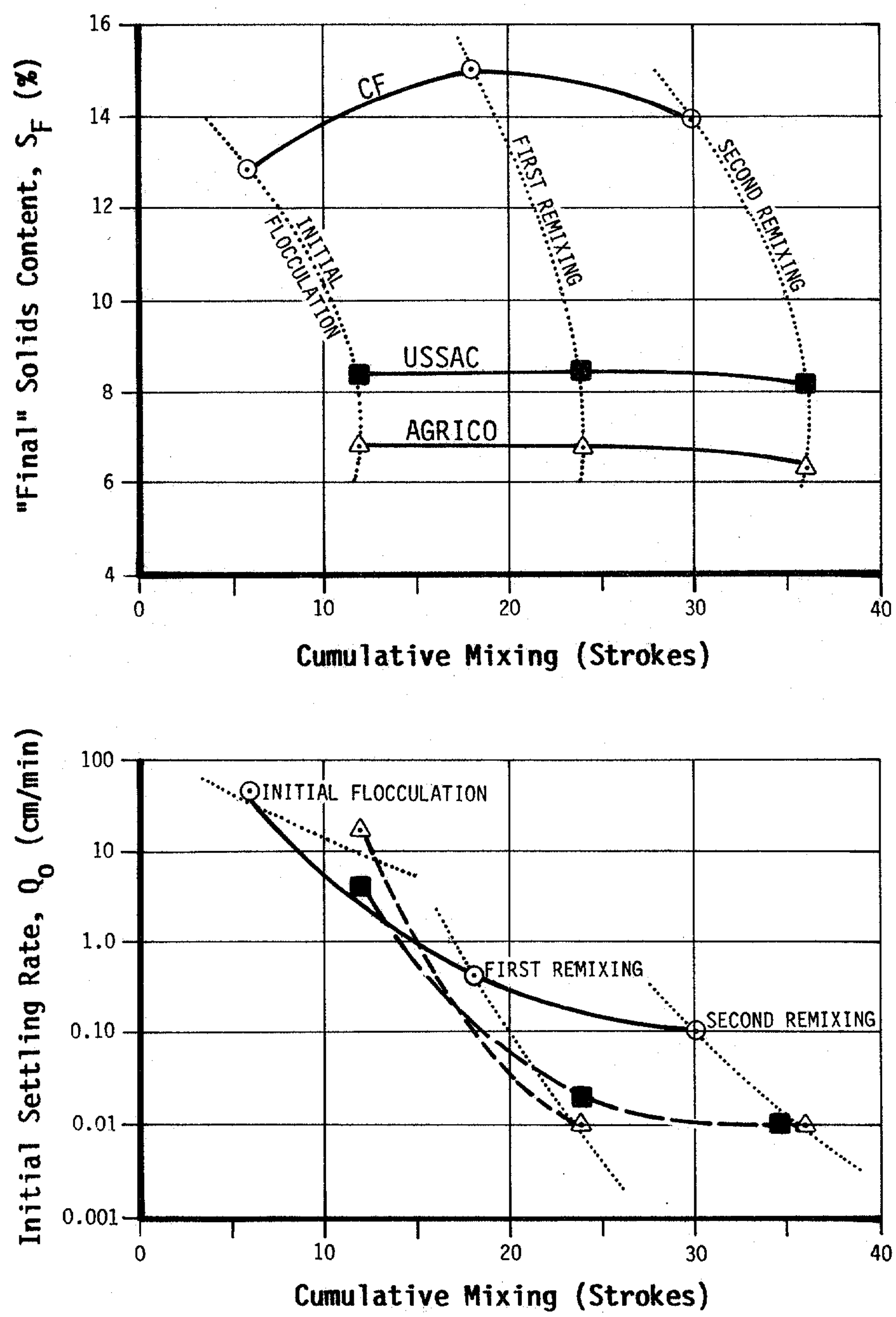
EFFECT OF INITIAL SOLIDS CONTENT ON SETTLING RATE OF PHOSPHATIC CLAYS AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 3-11



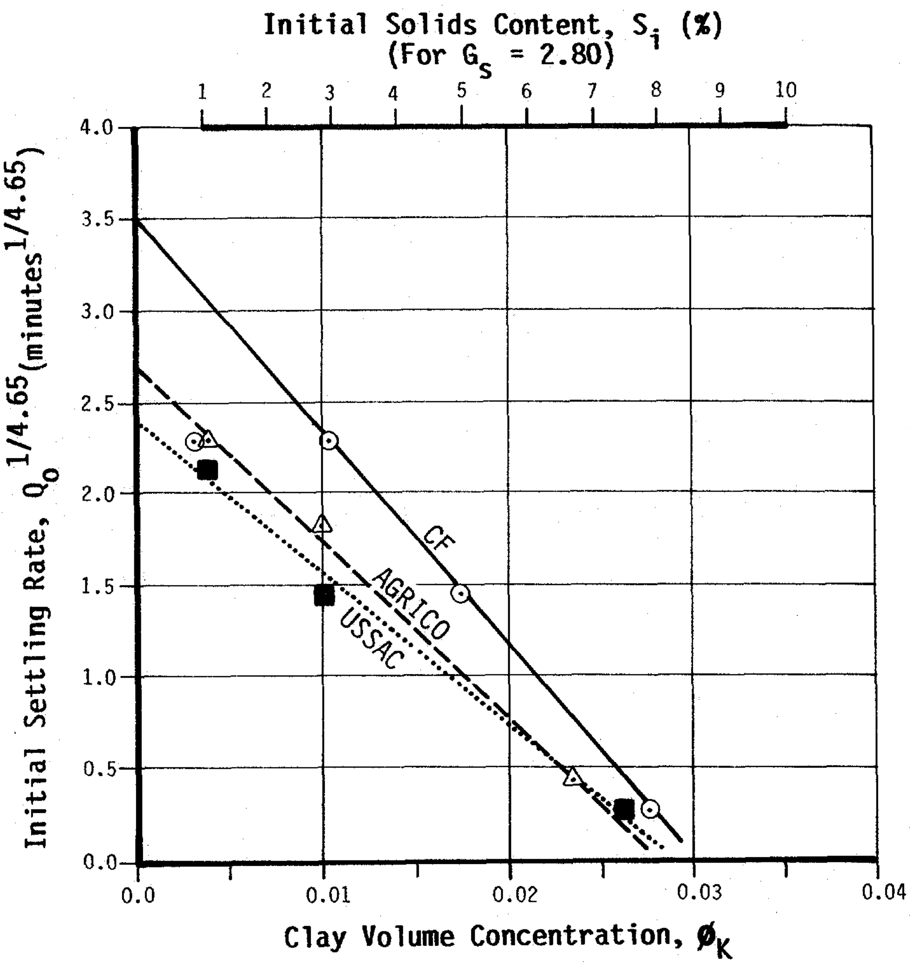
EFFECT OF MIXING DURING FLOCCULATION ON SETTLING BEHAVIOR OF CF MINING-HARDEE PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT

FIGURE 3-12



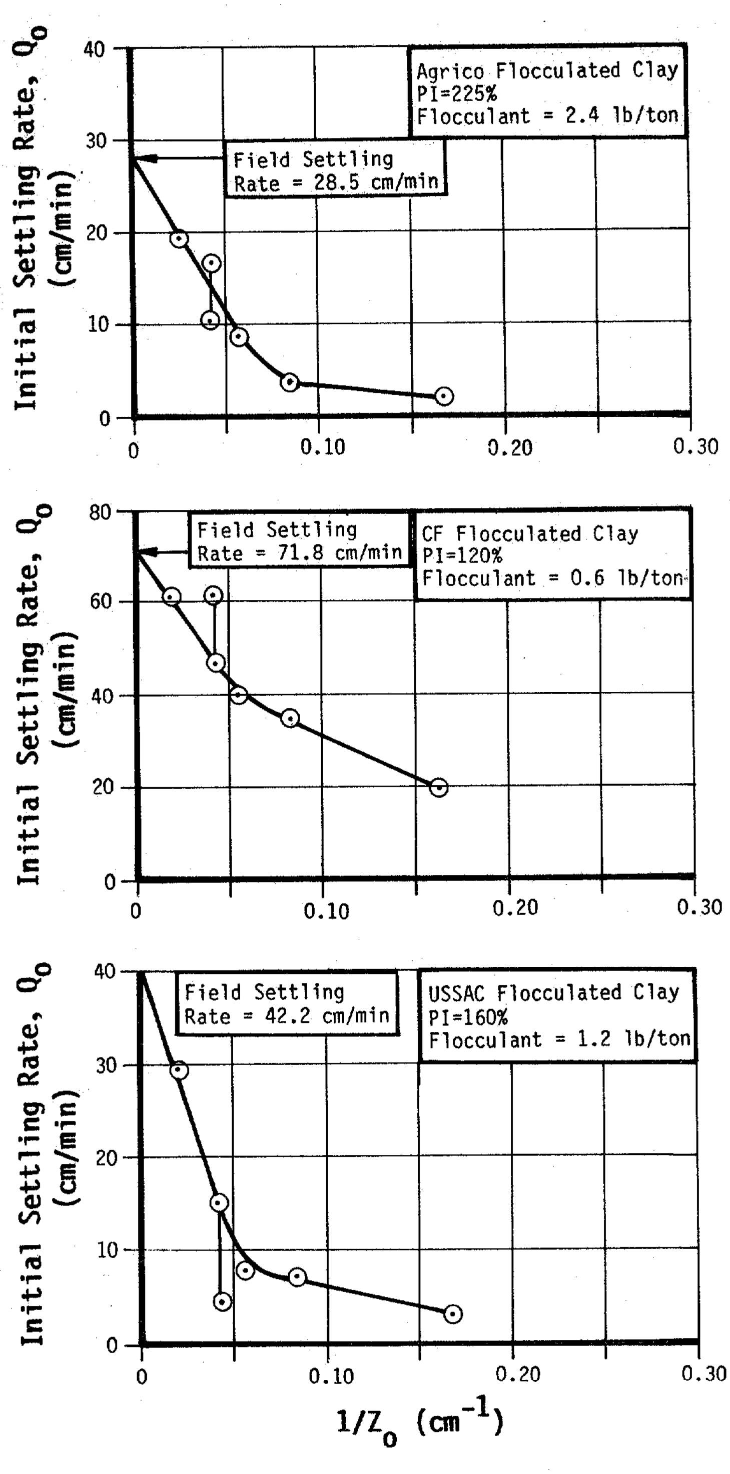
EFFECT OF MIXING AFTER FLOCCULATION ON SETTLING BEHAVIOR OF PHOSPHATIC CLAYS AT 3% INITIAL SOLIDS CONTENT AND OPTIMUM FLOCCULANT LOADING RATE

FIGURE 3-13



CLAY VOLUME CONCENTRATION VS. INITIAL SETTLING RATE FOR PHOSPHATIC CLAY AT OPTIMUM FLOCCULANT LOADING RATE

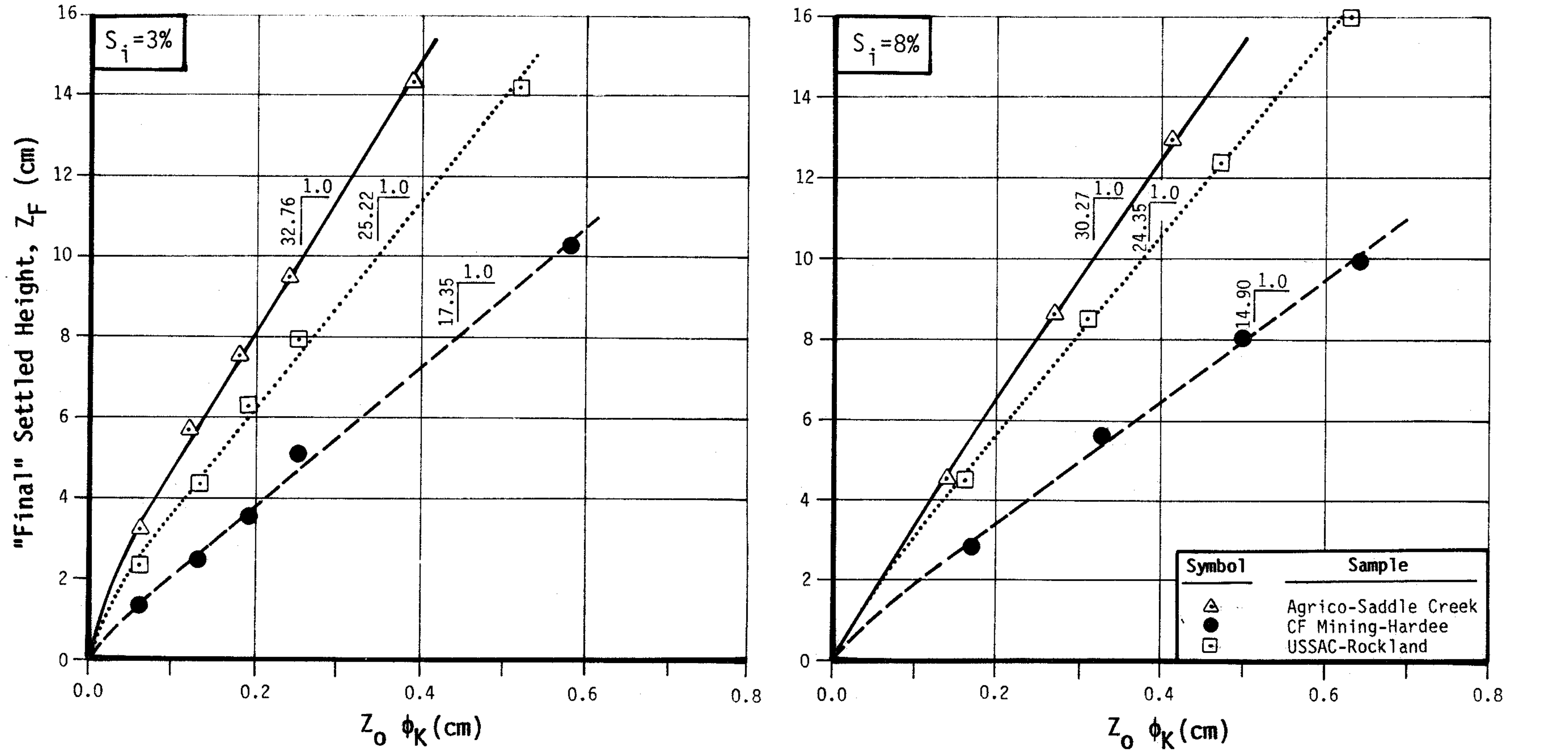
FIGURE 3-14



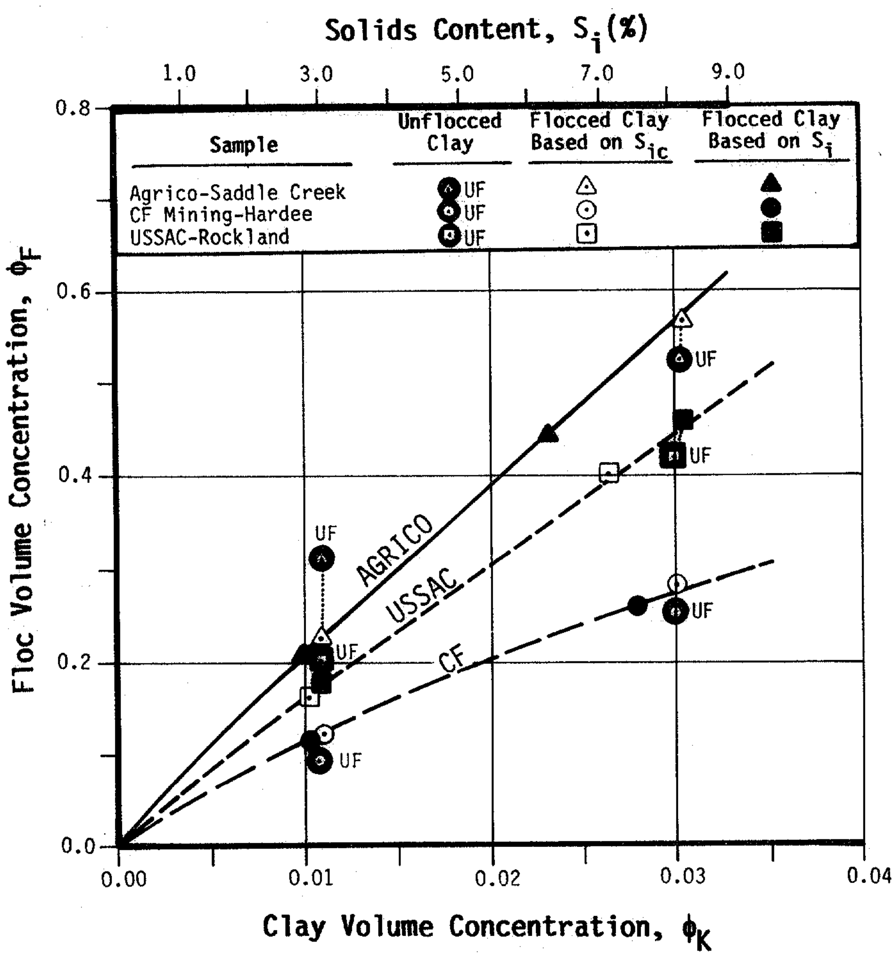
EFFECT OF HEIGHT ON INITIAL SETTLING RATE OF PHOSPHATIC CLAYS AT 3% INITIAL SOLIDS CONTENT AND OPTIMUM FLOCCULANT LOADING RATE

FIGURE 3-15

FIGURE 3-16

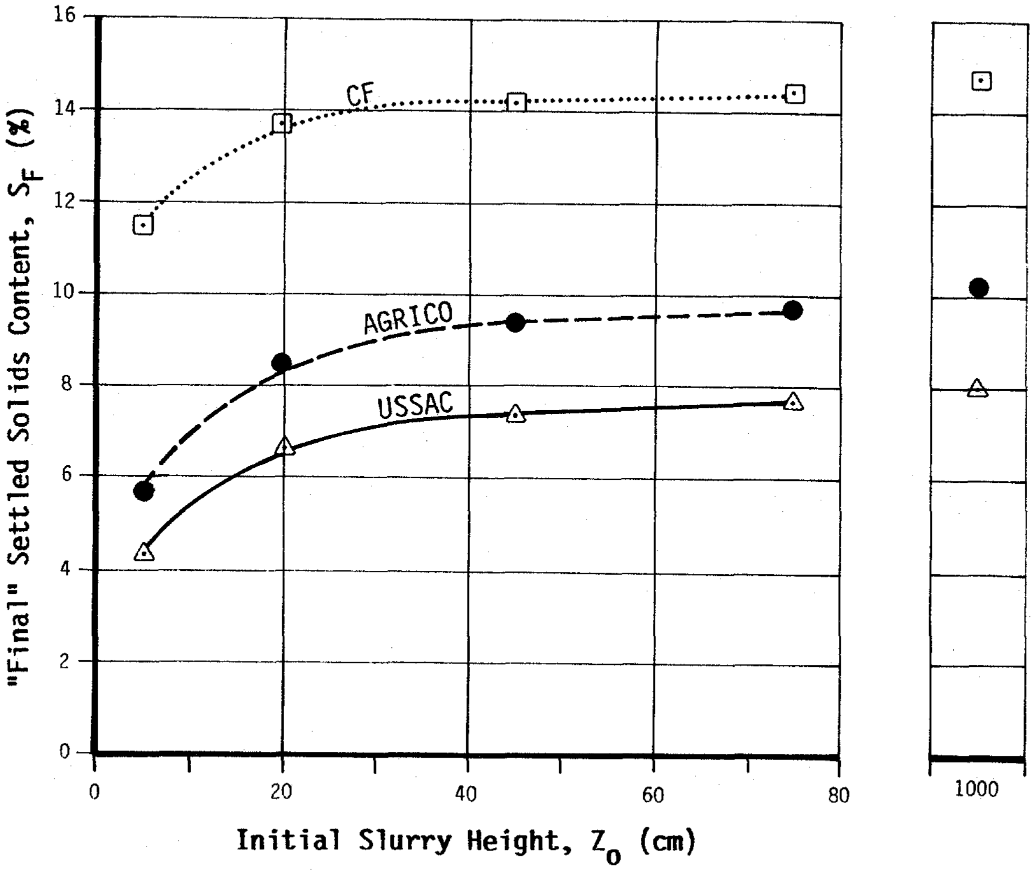


"FINAL" SETTLED HEIGHT VS $Z_o \phi_K$ FOR PHOSPHATIC CLAY AT 3% AND 8% INITIAL SOLIDS CONTENTS AND OPTIMUM FLOCCULANT LOADING RATE



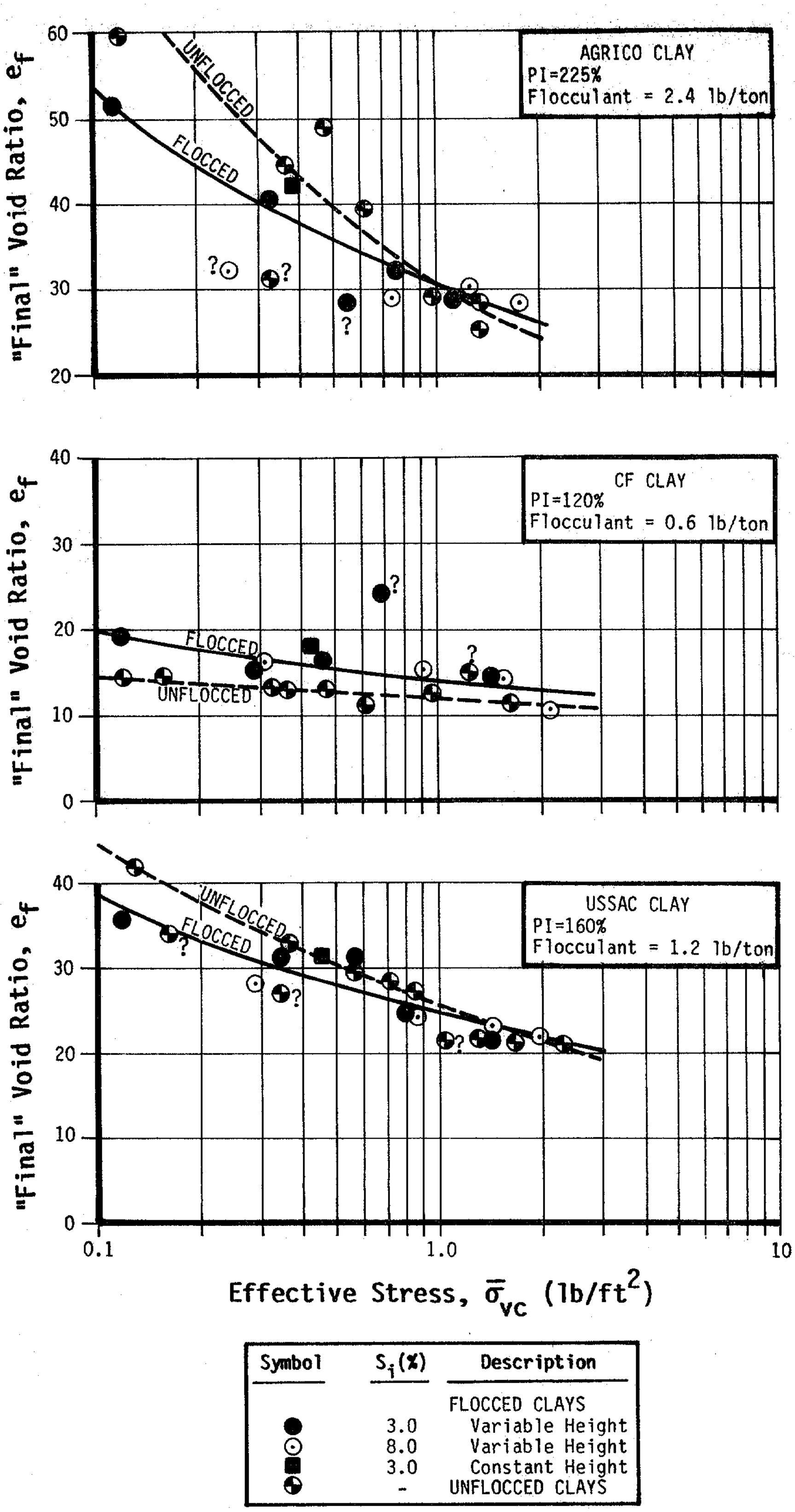
CLAY VOLUME CONCENTRATION VS. FLOC VOLUME CONCENTRATION FOR PHOSPHATIC CLAY AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 3-17



"FINAL" SETTLED SOLIDS CONTENT VS. INITIAL SLURRY HEIGHT FOR PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT AND OPTIMUM FLOCCULANT LOADING RATE

FIGURE 3-18



VOID RATIO VS. EFFECTIVE STRESS FOR PHOSPHATIC CLAY AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 3-19

Section 4

CONSOLIDATION BEHAVIOR OF FLOCCULATED PHOSPHATIC CLAYS

4.1 Introduction

Limited consolidation test results reported in the literature suggest that the compressibility and permeability of flocced and unflocced high plasticity phosphatic clays may be similar. Generally, however, flocced sediments are expected to be more "rigid" than unflocced sediments, due to more edge to face particle contacts. Accordingly flocced sediments are expected to display a lower compressibility and a higher void ratio at a given effective stress. The objective of the present investigation of the consolidation behavior of flocculated phosphatic clays, therefore, was to evaluate the effect of flocculation on the consolidation behavior of three selected phosphatic clays for which the consolidation properties of unflocced samples were well established. To achieve this objective, one slurry consolidation test was performed on each selected phosphatic clay flocced at the "optimum" flocculant loading rate as described in Section 3.4.3.

The results and evaluations of the slurry consolidation tests performed on the flocculated clays are presented in this section. As discussed in Section 1, phosphatic clays from the Agrico, CF and USSAC mines were selected for the flocculated clay slurry consolidation tests. These three clays were previously found (Volume 4) to display relatively poor, good and average consolidation properties, respectively, and should reflect the effect of flocculation on a wide range of phosphatic clays.

4.2 Test Methods and Procedures

Laboratory slurry consolidation tests were performed, interpreted and evaluated in accordance with the general test methods and procedures previously outlined in Volume 4, Sections 2.3.2 and 2.4.

After preparing the clay samples to an initial solids content, S_i, of 3%, the clay slurries were poured into the slurry consolidometers to the selected initial sample heights. Initial sample heights of 35.7, 53.0 and 47.1 cm were used for the Agrico, CF and USSAC clays, respectively. The clay was thoroughly mixed after placement within the column with a hand-held perforated plunger-type stirrer to achieve a homogeneous sample. The stirrer was then removed and a pre-measured quantity of NALCO 7877 flocculant in a 0.10% solution by volume was added to the suspension in one increment to produce flocculant loading rates of 2.4, 0.6 and 1.2 lb/ton of clay for the Agrico, CF and USSAC clays, respectively. The stirrer was replaced into the consolidometer column after addition of the flocculant and the suspension was slowly “stroked” up and down until the maximum effect of the flocculant (i.e., floc size) was visually observed. The stirrer was then removed from the column and the height of the interface with time was monitored. When no further settling of the interface was observed, an initial load of 0.001 kg/cm^2 was applied to the sample. The test was then continued as previously described in Volume 4, Section 2.3.2 for unflocced clay.

The slurry consolidation tests were performed and evaluated using the square root of time curve fitting method. Previous test results presented in Volume 4, Section 3.2.4.2, have shown that the curve fitting technique does not have a significant effect on the interpretation of phosphatic clay test results. A summary of results for each test is presented in Appendix G, Tables G-1, G-2 and G-3.

4.3 Effect of Flocculation on Consolidation Behavior

The properties of interest in modeling the consolidation behavior of flocculated clays within settling areas include: initial void ratio; void ratio as a function of effective stress; coefficient of permeability as a function of void ratio; coefficient of consolidation; and coefficient of secondary compression. Each of these properties are subsequently discussed below.

4.3.1 "Initial" Void Ratio

Typically, the "initial" void ratio (or solids content) for use in consolidation analyses is selected as the 30-day "final" void ratio determined from laboratory settling tests starting from the initial solids content expected for the slurry (generally 3 to 4%) and flocced at the selected flocculant loading rate. For a flocced clay, the "final" void ratio will depend on the flocculant loading rate, type of flocculant used and method of mixing the clay and flocculant.

In general, a flocculated clay is expected to yield a slightly higher "final" settled void ratio (or slightly lower settled solids content) than an unflocced clay due to the formation of larger flocs.* As previously shown in Section 3.4.1, this behavior was observed for the low to medium plasticity CF and USSAC phosphatic clays, whereas the high plasticity Agrico phosphatic clay displayed the reverse trend of a very slight decrease in "final" settled void ratio (or increase in solids content). For preliminary evaluations, the relationship previously presented in Figure 3-2 can be used to estimate the relative effect of flocculation on the "final" settled void ratio of phosphatic clays of various plasticity. The relationship, however, is strictly applicable for NALCO 7877 flocculant added to the clay in accordance with the described test methods.

4.3.2 Void Ratio Versus Effective Stress Relationship

The void ratio versus effective stress relationships developed for the Agrico, CF and USSAC phosphatic clays at the "optimum" flocculant loading rate are presented in Figures 4-1, 4-2 and 4-3. The void ratio versus effective stress relationships developed previously (Volume 4, Section 3.2.2) for unflocced clays are also included for comparison. As shown, the highly plastic Agrico clay void ratio versus effective stress behavior is essentially identical whether the clay is flocced or unflocced. The behavior of the medium plasticity USSAC phosphatic

*Solids content, S, and void ratio, e, are related by the expression: $e = (\rho(1-S/S))$, where ρ is the specific gravity of clay solids.

clay is affected slightly, and the behavior of the relative low plasticity CF phosphatic clay is significantly affected. As expected, the clays that are affected display a higher void ratio at a given effective stress when flocced than when unflocced. The effect of flocculation on the void ratio versus effective stress behavior appears to decrease with increasing clay plasticity. Accordingly, the use of a unique relationship between void ratio and effective stress for flocced and unflocced clays is not always justified.

4.3.2.1 Simplified Form of Void Ratio Versus Effective Stress Relationship

For convenience, a log-log linear relationship between void ratio and effective stress is often used for predictions of consolidation behavior, rather than actual point-to-point data as measured during consolidation tests. There is no theoretical basis for selection of a log-log linear relationship, but only empirical evidence typically showing that such a relationship yields a good statistical fit to laboratory measured data. Further, the relationship is easily handled mathematically because it is characterized by only two coefficients. The equation is of the form:

$$e = \alpha \bar{\sigma}_{vc}^{\beta} \qquad (1)$$

The coefficients α and β have also been correlated with plasticity, as previously shown in Volume 4, Section 3.2.2.2, further making Equation 1 a useful expression of consolidation behavior. The coefficient α is the intercept of the log-log linear curve at an effective stress of unity and, hence, depends on the units of stress. The coefficient β is the slope of the log-log line characterizing compressibility.

Figure 4-4 presents least squares log-log linear regression analyses of void ratio versus effective stress consolidation test data for the Agrico, CF and USSAC clays at the "optimum" flocculant loading rate. As shown, below the "initial" void ratio the measured data agrees well with a linear log-log void ratio versus effective stress relationship. Hence, the use of Equation 1 to model the compressibility of flocced phosphatic clays appears justified.

4.3.2.2 Correlation Between Plasticity and Compressibility

The coefficients α and β determined for each of the clays at the "optimum" flocculant loading rate and the previously determined α and β coefficients for unflocced clays (Volume 4, Section 3.2.2.2) are summarized below and shown in Figure 4-4.

	Coefficient α		Coefficient β	
Sample	Unflocced α_{uf}	Flocced α_f	Unflocced β_{uf}	Flocced β_f
Agrico-Saddle Creek	4.094	3.925	-0.293	-0.311
CF Mining-Hardee	2.376	2.893	-0.233	-0.282
USSAC-Rockland	3.206	3.581	-0.284	-0.315

Where: the α and β coefficients are for an equation of the form: $e = \alpha \bar{\sigma}_{vc}^{\beta}$, where e is the void ratio and $\bar{\sigma}_{vc}$ is the effective stress in units of kg/cm^2.

The α and β coefficients for the highly plastic Agrico clay are generally similar for the flocced and unflocced samples. The α and β coefficients for the CF and USSAC flocced clays, however, are higher in absolute magnitude than for unflocced clay. Physcially, a higher $|\beta|$ parameter indicates that flocced clays undergo a greater change in void ratio for a given change in effective stress. A higher α parameter means that flocced clays display a higher void ratio at a given effective stress, in this case at a stress of 1.0 kg/cm^2.

The ratio of the flocced to unflocced α coefficients (α_f/α_{uf}) and the flocced to unflocced β coefficients (β_f/β_{uf}), or normalized compressibility parameters, for each clay are summarized below:

Sample	PI (%)	"Optimum" Flocculant Loading Rate (lb/ton clay)	α_f/α_{uf}	β_f/β_{uf}
Agrico-Saddle Creek	225	2.4	0.96	1.06
CF Mining-Hardee	115	0.6	1.22	1.21
USSAC-Rockland	160	1.2	1.12	1.11

As shown in Figure 4-5, the normalized compressibility coefficients α_f/α_{uf} and β_f/β_{uf} for clays at the "optimum" flocculant loading rate increase with decreasing plasticity index, implying a greater effect of flocculation on clays of lower plasticity. The ratios also appear to be similar for both parameters, displaying a unique relationship with plasticity index. Physically, a higher α_f/α_{uf} ratio with decreasing plasticity index indicates that a flocced clay will display a higher void ratio at a given effective stress, in this case 1.0 kg/cm^2, than an unflocced clay with the effect increasing with decreasing plasticity index. A higher β_f/β_{uf} ratio with decreasing plasticity index indicates that a flocced clay will display a greater change in void ratio for a given increment of effective stress than an unflocced clay, with the effect increasing with decreasing plasticity index.

The effect of flocculation on the void ratio versus effective stress behavior of a phosphatic clay can be estimated using the recommended relationship in Figure 4-5. Note, however, that the relationship is strictly applicable for NALCO 7877 flocculant at the specified loading rate added to the clay in accordance with the described test methods.

4.3.2.3 Correlation Between Void Ratio from Settling Tests and Compressibility

The 30-day "final" settled void ratio, e_f, determined from laboratory settling tests corresponds to the "initial" void ratio, e_i, used in consolidation analyses. Correlations between the α and β parameters and the "final" settled void ratio, e_f, were previously shown for unflocced clays in Volume 4, Section 3.2.2.3, to be useful for estimating α and β parameters from settling test data.

Correlations between the α and β parameters and the "final" settled void ratio for flocced clay are presented in Figure 4-6. The correlations previously found for unflocced clay are also presented for comparison. As shown, for a given "final" settled void ratio the correlations yield higher α and β parameters for flocced clay than for unflocced clay. These results indicate that the compressibility of flocced clays is influenced by the induced edge-to-face particle orientations resulting from flocculation in addition to the effect on "final" settled void ratio, otherwise a unique relationship would have existed between α and β and the "final" settled void ratio for both flocced and unflocced clay. Physically, the two correlations show that a flocced clay which settles to a given "final" void ratio will compress less and remain at a higher void ratio than an unflocced clay.

The correlations in Figure 4-6 can be used to estimate the effect of flocculation on the α and β parameters for flocced clays. The correlations, however, are strictly applicable for NALCO 7877 flocculant at the specified loading rate added to the clay in accordance with the described test methods.

4.3.3 Coefficient of Permeability

The void ratio versus coefficient of permeability relationships developed for the Agrico, CF and USSAC phosphatic clays at the "optimum" flocculant loading rate are presented in Figures 4-7, 4-8 and 4-9. The coefficients of permeability used to develop the relationships were calculated using the square root of time curve fitting method ($k\sqrt{t}$) plotted at the average void ratio, e_{50}, for the load increment. The coefficients of permeability used in the evaluations are listed in Appendix G, Tables G-1 through G-3. The void ratio versus coefficient of permeability relationships developed previously (Volume 4, Section 3.2.3) for the unflocced clays are also included for comparison. As shown, the void ratio versus coefficient of permeability relationships for flocced and unflocced clay appear similar, with no visibly obvious differences or monotonic trends in behavior as displayed by the void ratio versus effective stress relationships. Accordingly, it appears that the assumption of an approximately unique relationship between void ratio and coefficient of permeability for flocced and unflocced clays may be justified.

4.3.3.1 Simplified Form of Void Ratio Versus Coefficient of Permeability Relationship

Log void ratio versus log coefficient of permeability relationships are often used in the prediction of the consolidation behavior of phosphatic clays. This form is selected because the relationship is characterized by only two coefficients in an equation of the form:

$$k = \gamma e^{\delta} \quad (2)$$

As discussed in Volume 4, Section 3.2.3.1, there is no basis for selection of a log-log linear relationship, other than empirical evidence indicating that the relationship usually statistically yields the best fit curve to a series of data.

Figure 4-10 presents least squares log-log linear regression analyses of void ratio versus coefficient of permeability data for the Agrico, CF and USSAC clays at the "optimum" flocculant loading rate. As shown, the measured data agree well with linear log void ratio versus log coefficient of permeability relationships. Hence, the use of Equation 2 to model the permeability of flocced phosphatic clays appears justified.

4.3.3.2 Comparison of Flocced and Unflocced Coefficient of Permeability Versus Void Ratio Relationships

The coefficients Υ and δ determined for each of the clays at the "optimum" flocculant loading rate and the previously determined Υ and δ coefficients for unflocced clays (Volume 4, Section 3.2.3.1) are summarized below and in Figure 4-10.

Sample	Coefficient Υ Unflocced Υ_{uf}	Coefficient Υ Flocced Υ_f	Coefficient δ Unflocced δ_{uf}	Coefficient δ Flocced δ_f
Agrico-Saddle Creek	$6.21x10^{-10}$	$1.18x10^{-9}$	3.10	2.80
CF Mining-Hardee	$5.44x10^{-10}$	$4.31x10^{-10}$	4.08	3.86
USSAC-Rockland	$5.94x10^{-10}$	$2.42x10^{-10}$	3.34	2.42

Where: the Υ and δ coefficients are for an equation of the form: $k = \Upsilon e^{\delta}$, where e is void ratio and k is the coefficient of permeability determined from the square root of time curve fitting method in units of cm/sec.

As shown in Figure 4-10, the void ratio versus coefficient of permeability relationship obtained from these coefficients are generally similar, although the relationship for the flocced CF clay consistently yields a slightly lower coefficient of permeability at a given void ratio than the relationship for unflocced clay. For comparison, the coefficients of permeability obtained from the log-log linear regression analyses at selected void ratios are given below for flocced, k_f, and unflocced, k_{uf}, clay:

Sample	Void Ratio, e: 20	10	5	2
Agrico-Saddle Creek				
k_f, cm/sec	$5.22x10^{-6}$	$7.49x10^{-7}$	$1.07x10^{-7}$	$8.22x10^{-9}$
k_{uf}, cm/sec	$6.70x10^{-6}$	$7.82x10^{-7}$	$9.12x10^{-8}$	$5.32x10^{-9}$
k_f/k_{uf}	0.78	0.96	1.17	1.55
CF Mining-Hardee				
k_f, cm/sec	$4.58x10^{-5}$	$3.15x10^{-6}$	$2.16x10^{-7}$	$6.27x10^{-9}$
k_{uf}, cm/sec	$1.11x10^{-4}$	$6.54x10^{-6}$	$3.87x10^{-7}$	$9.20x10^{-9}$
k_f/k_{uf}	0.41	0.48	0.56	0.68
USSAC-Rockland				
k_f, cm/sec	$2.64x10^{-5}$	$1.80x10^{-6}$	$1.22x10^{-7}$	$3.53x10^{-9}$
k_{uf}, cm/sec	$1.32x10^{-5}$	$1.30x10^{-6}$	$1.28x10^{-7}$	$6.01x10^{-9}$
k_f/kuf	2.00	1.38	0.95	0.59

As shown above and in Figure 4-11, the coefficient of permeability ratios for flocced and unflocced clays, k_f/k_{uf}, vary from 0.4 to 2.0, which are judged relatively small changes considering the general difficulty in measuring coefficients of permeability and the orders of magnitude change in the coefficient of permeability occurring over the void ratio range of interest. Further, no consistent trend between permeability and void ratio occurs as a function of clay plasticity, although for each clay a monotonic trend is observed as a function of void ratio. Accordingly, it appears that at a given void ratio the coefficient of permeability of flocced and unflocced clays are slightly different, but no unique correlation was found to exist for the three tested clays.

4.3.3.3 Comparison of Flocced and Unflocced Coefficient of Permeability Versus Effective Stress Relationships

The log-log linear relationships $e = \alpha\bar{\sigma}_{vc}^{\beta}$ and $k = \Upsilon e^{\delta}$ can be used to establish a log-log relationship between permeability and effective stress related by the compressibility and permeability parameters α, β, ϒ and δ in the following manner:

$$k = \Upsilon\alpha^{\delta}\bar{\sigma}_{vc}^{\beta\delta} \qquad (3)$$

Using Equation 3 and the α, β, γ and δ parameters established for the flocced and unflocced clays, the coefficient of permeability for each clay at a given effective stress can be compared as follows:

Sample	Effective Stress, $\bar{\sigma}_{vc}$ (kg/cm^2) 0.003	0.03	0.30	3.0
Agrico-Saddle Creek				
k_f, cm/sec	$8.61x10^{-6}$	$1.16x10^{-6}$	$1.55x10^{-7}$	$2.11x10^{-8}$
k_{uf}, cm/sec	$9.39x10^{-6}$	$1.14x10^{-6}$	$1.37x10^{-7}$	$1.68x10^{-8}$
k_f/k_{uf}	0.92	1.01	1.00	0.97
CF Mining-Hardee				
k_f, cm/sec	$1.47x10^{-5}$	$1.21x10^{-6}$	$1.00x10^{-7}$	$7.58x10^{-9}$
k_{uf}, cm/sec	$5.78x10^{-6}$	$6.14x10^{-7}$	$6.26x10^{-8}$	$5.99x10^{-9}$
k_f/k_{uf}	2.54	1.97	1.60	1.27
USSAC-Rockland				
k_f, cm/sec	$4.02x10^{-5}$	$2.43x10^{-6}$	$1.43x10^{-7}$	$8.39x10^{-9}$
k_{uf}, cm/sec	$5.26x10^{-6}$	$6.43x10^{-7}$	$7.75x10^{-8}$	$9.59x10^{-9}$
k_f/k_{uf}	7.64	3.78	1.85	0.87

At the same effective stress, the coefficient of permeability ratios for flocced and unflocced clays, k_f/k_{uf}, vary from about 0.9 to 7.6, but are generally greater than 1.0. This result implies that at a given effective stress flocced clays display a slightly greater coefficient of permeability than unflocced clays. This behavior occurs because at a given effective stress the void ratio of a clay when flocced is generally higher than when unflocced. Accordingly, it appears that at a given effective stress the coefficient of permeability of a flocced clay is slightly greater than that of an unflocced clay. No unique correlation, however, was found relating k_f/k_{uf} and clay plasticity.

4.3.3.4 Comparison of Measured and Backfigured Coefficients of Permeability

A comparison of backfigured coefficients of permeability from the square root of time curve fitting method with measured coefficients of permeability from constant-head tests performed during slurry consolidation tests (as described in Volume 4, Section 2.4.4) is presented in Figure 4-12. The corresponding γ and δ parameters for each relationship are included on the figure and presented below.

Sample	Backfigured Coefficient of Permeability, $k(\sqrt{t})$		Measured Coefficient of Permeability, k_m	
	γ	δ	γ	δ
Agrico-Saddle Creek	1.18×10^{-9}	2.80	1.44×10^{-9}	2.88
CF Mining-Hardee	4.31×10^{-10}	3.86	1.65×10^{-9}	3.25
USSAC-Rockland	2.42×10^{-10}	3.87	1.64×10^{-9}	3.15

Where: the γ and δ coefficients are for an equation of the form: $k = \gamma e^{\delta}$, where e is void ratio and k is the coefficient of permeability in units of cm/sec.

For each clay the measured coefficient of permeability, k_m, is generally slightly greater than the backfigured coefficient of permeability, $k(\sqrt{t})$. For comparison, the calculated and measured coefficients of permeability and the ratio of measured to calculated values ($k_m/k(\sqrt{t})$) for selected void ratios of 2, 5, 10 and 20 are presented below:

Sample	Void Ratio			
	2	5	10	20
Agrico-Saddle Creek				
$k(\sqrt{t})$*	8.22×10^{-9}	1.07×10^{-7}	7.49×10^{-7}	5.22×10^{-6}
k_m**	1.06×10^{-8}	1.49×10^{-7}	1.10×10^{-6}	8.07×10^{-6}
$k_m/k(\sqrt{t})$	1.29	1.39	1.47	1.55
CF Mining-Hardee				
$k(\sqrt{t})$*	6.27×10^{-9}	2.16×10^{-7}	3.15×10^{-6}	4.58×10^{-5}
k_m**	1.58×10^{-8}	3.11×10^{-7}	2.97×10^{-6}	2.84×10^{-5}
$k_m/k(\sqrt{t})$	2.52	1.44	0.94	0.62

Sample	Void Ratio 2	5	10	20
USSAC-Rockland				
$k(\sqrt{t})$*	$3.54\text{x}10^{-9}$	$1.23\text{x}10^{-7}$	$1.80\text{x}10^{-6}$	$2.64\text{x}10^{-5}$
k_m**	$1.46\text{x}10^{-8}$	$2.63\text{x}10^{-7}$	$2.35\text{x}10^{-6}$	$2.09\text{x}10^{-5}$
$k_m/k(\sqrt{t})$	4.12	2.14	1.31	0.79

*$k(\sqrt{t})$ is the coefficient of permeability backfigured from the square root of time method from an equation of the form $k(\sqrt{t}) = \Upsilon e^{\delta}$ where Υ and δ are regression coefficients given for units of cm/sec.

**k_m is the measured coefficient of permeability determined from an equation of the form $k_m = \Upsilon e^{\delta}$ where Υ and δ are regression coefficients given for units of cm/sec.

The ratio of the measured to the backfigured coefficient of permeability ranges from a low of about 0.6 to a high of 4.1, although $k_m/k(\sqrt{t})$ is generally greater than 1.0. The average relationship for the three clays is $k_m/k(\sqrt{t}) = 1.63 \pm 0.94$. Hence, the calculated coefficients of permeability from the square root of time method are judged in reasonable agreement with measured coefficients of permeability, although there appears to be a consistent trend of k_m being slightly greater than $k(\sqrt{t})$.

4.3.4 Coefficient of Consolidation

The coefficient of consolidation, c_v, governs the time rate at which consolidation occurs. The coefficient of consolidation during a load increment was determined based on Terzaghi's theory using graphical curve fitting procedures applied to plots of sample height versus the square root of time ($\sqrt{t}$ method). The coefficients of consolidation determined from this method are listed in Appendix G, Tables G-1 through G-3.

4.3.4.1 Effect of Stress Level

Figure 4-13 presents individual plots of the coefficient of consolidation versus effective stress for each of the three tested clays. An average representative value for $c_v(\sqrt{t})$ is also noted for each clay. The coefficient of consolidation clearly varies from the average by factors ranging from about 0.3 to 1.8 times the average value. No universally consistent monotonic trends occur in the data, however, suggesting that the variability may be due to testing variables rather than an inherent material property. Part of the variability resulting from relatively high coefficients of consolidation, for example, is due to the amount of secondary compression during a previous load increment, which would increase the initial rate of consolidation in the subsequent load increment.

4.3.4.2 Effect of Log-Log Relationships Used to Model Consolidation Behavior

As previously outlined, log-log relationships between void ratio and effective stress, and the coefficient of permeability and void ratio are often used to model the consolidation behavior of phosphatic clays. These relationships:

$$e = \alpha \bar{\sigma}^{\beta} \quad (4)$$

$$k = \gamma e^{\delta} = \gamma \alpha^{\delta} \bar{\sigma}^{\beta\delta} \quad (5)$$

can be used to determine the coefficient of consolidation, c_v. The relationship between c_v and effective stress is obtained by: (i) determining the coefficient of volume change, m_v, by taking the derivative of Equation 4 and expressing it in terms of strain rather than void ratio; and (ii) inserting the relationships for k and m_v as a function of effective stress into the Terzaghi relationship between the coefficient of consolidation and the coefficient of volume change:

$$c_v = k/(m_v \gamma_w) \quad (6)$$

When $\bar{\sigma}$ is expressed in units of kg/cm^2 and k in units of cm/sec, the resulting expression for c_v in units of cm^2/sec is:

$$c_v = \left[\frac{1000\, \gamma \alpha^{(\delta-1)}}{-\beta}\right] \left[\bar{\sigma}^{(1+\beta\delta)} (\bar{\sigma}^{(-\beta)} + \alpha)\right] \quad (7)$$

The variation of c_v based on Equation 7 is illustrated for each flocced clay in Figure 4-13. As shown, each flocculated clay displays a different trend of c_v with effective stress. The Agrico clay displays an increase in c_v from $8x10^{-5}$ to $3x10^{-4}$ cm^2/sec over the stress range of 0.001 to 4.0 kg/cm^2, the CF clay coefficient of consolidation decreases slightly with increasing stress level but is relatively constant at $1.5x10^{-4}$ cm^2/sec, and the USSAC clay displays a decrease in c_v from $5x10^{-4}$ to $1.1x10^{-4}$ cm^2/sec over the stress range of 0.001 to 4.0 kg/cm^2. Although the measured values of c_v are variable, the relationship predicted from Equation 7 agrees reasonably well with trends in the measured data.

Note that c_v backfigured from Equation 7 will be about 30% (at low effective stresses) to 15% (at high effective stresses) lower than backfigured incrementally for a load increment ratio of 1. This is because Equation 7 is based on the tangency to the compressibility relationship rather than the secant value used in incremental evaluations. Hence, c_v backfigured from Equation 7 should be increased by about 20 to 25% for consistency with c_v obtained by curve fitting techniques.

4.3.4.3 Comparison of Flocced and Unflocced Coefficient of Consolidation Versus Effective Stress Relationships

The coefficient of consolidation versus effective stress relationships developed for the flocced clays and previously established for unflocced clays (Volume 4, Section 3.2.4.3) using Equation 7 are compared in Figure 4-14. As shown, the flocced and unflocced relationships for the Agrico clay are similar. This result was expected because the coefficient of permeability and compressibility were previously shown to be similar for flocced and unflocced Agrico clay.

The coefficient of consolidation of flocced CF and USSAC clay at a given stress is generally higher than for unflocced clay. This results because the coefficient of permeability of flocced clay at a given effective stress is generally greater than for unflocced clay whereas the compressibility is only slightly greater. Accordingly, based on Equation 6, because k_f increases relatively more than m_v the resulting effect is an increase in the coefficient of consolidation.

4.3.5 Coefficient of Secondary Compression

The coefficient of secondary compression, C_α, governs the magnitude of long-term drained creep settlements which occur after consolidation is complete. Secondary compression is generally modelled by a linear relationship between strain (or void ratio) and log time, and is defined by the slope of the strain versus log time line as previously described in Volume 4, Section 2.4.5. The coefficients of secondary compression determined from the slurry consolidation tests on the flocced clays are listed in Appendix G, Tables G-1 through G-3. The values of the coefficient of secondary compression are based on a strain calculated from the sample height at the beginning of the load increment rather than the initial sample height at the beginning of the test.

Figure 4-15 illustrates the relationship between measured coefficients of secondary compression and void ratio for phosphatic clays at the "optimum" flocculant loading rate. The previously established (Volume 4, Section 3.2.5) void ratio versus coefficient of secondary compression relationships are also included for comparison. As shown, there is considerable variability in the measured values with C_α ranging from 0.6 to 2.7%. An empirical correlation between C_α and void ratio often used in practice for natural clays is also presented in Figure 4-15 (NAVFAC DM-7, 1971). The measured values of C_α are consistently below those determined from the empirical correlation. Hence, the phosphatic clays do not display as high a degree of secondary compression as normally expected for highly plastic clays. Although no unique relationship is evident between void ratio and coefficient of secondary compression, most values fall within the range of $C_\alpha = 0.15e$ to $C_\alpha = 0.5e$.

As a general guideline, a C_α of $1.4\% \pm 0.6\%$ appears reasonable for the flocced clays. This average value is 1.4 times higher than the previously recommended C_α of $1.0\% \pm 0.3\%$ for unflocced clays. Hence, the coefficient of secondary compression of flocced clays appears slightly higher than for unflocced clay.

4.4 Summary and Practical Implications

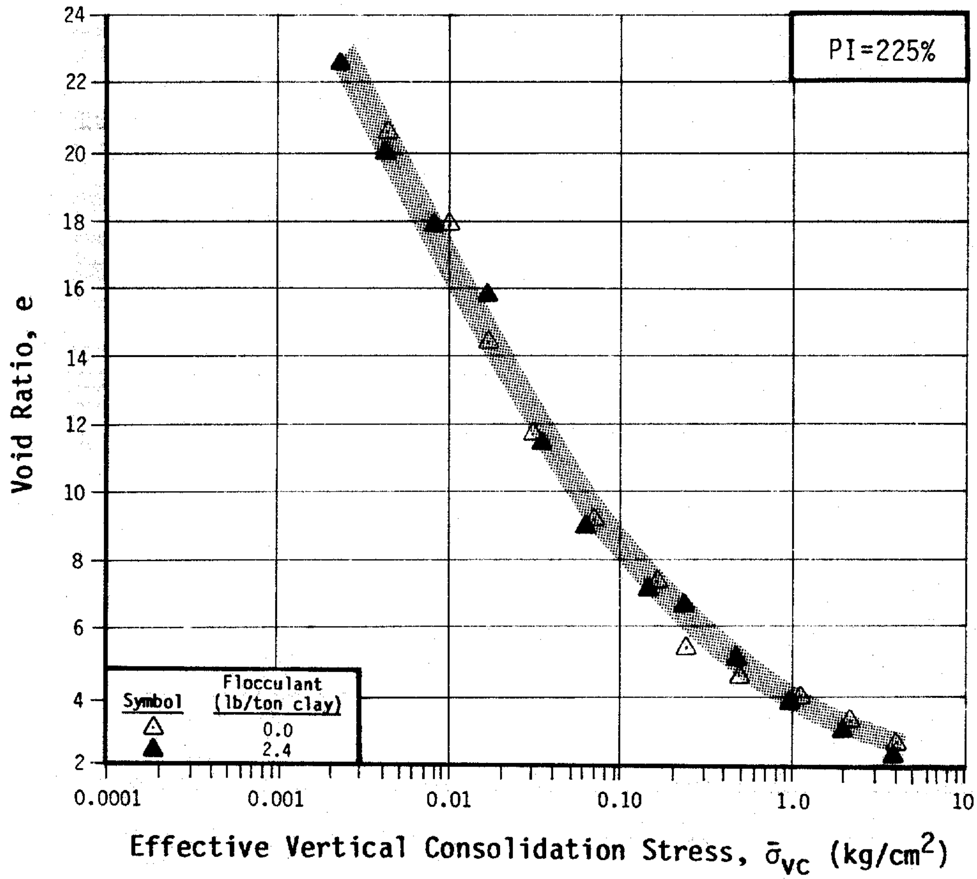
Slurry consolidation tests performed on flocculated phosphatic clays indicated a range of effects of flocculation on consolidation behavior. The significant findings and practical implications developed from the investigation are summarized below. Note, however, that these findings are applicable strictly for NALCO 7877 flocculant at the specified loading rate added to the clay in one increment in accordance with the described test methods and procedures. Different findings may result for other flocculants, loading rates and flocculation methods. Nevertheless, the findings are considered reasonable for use as a guide in evaluating the potential effects of flocculation on consolidation behavior.

The assumption of a unique void ratio versus effective stress relationship for flocced and unflocced clays was determined not to be always justified. The experimental data indicate that relatively high plasticity phosphatic clays may display a unique relationship, but low to medium plasticity phosphatic clays yield a higher void ratio at a given effective stress when flocced than when unflocced.

The concept of a unique void ratio versus coefficient of permeability relationship for flocced and unflocced clays was found to be reasonably justified. Deviations from the unique relationship at a given void ratio were relatively small, **but** tended to increase with decreasing clay plasticity. At a given effective stress, however, the coefficient of permeability of a flocced Clay tends to be higher than that of unflocced clay.

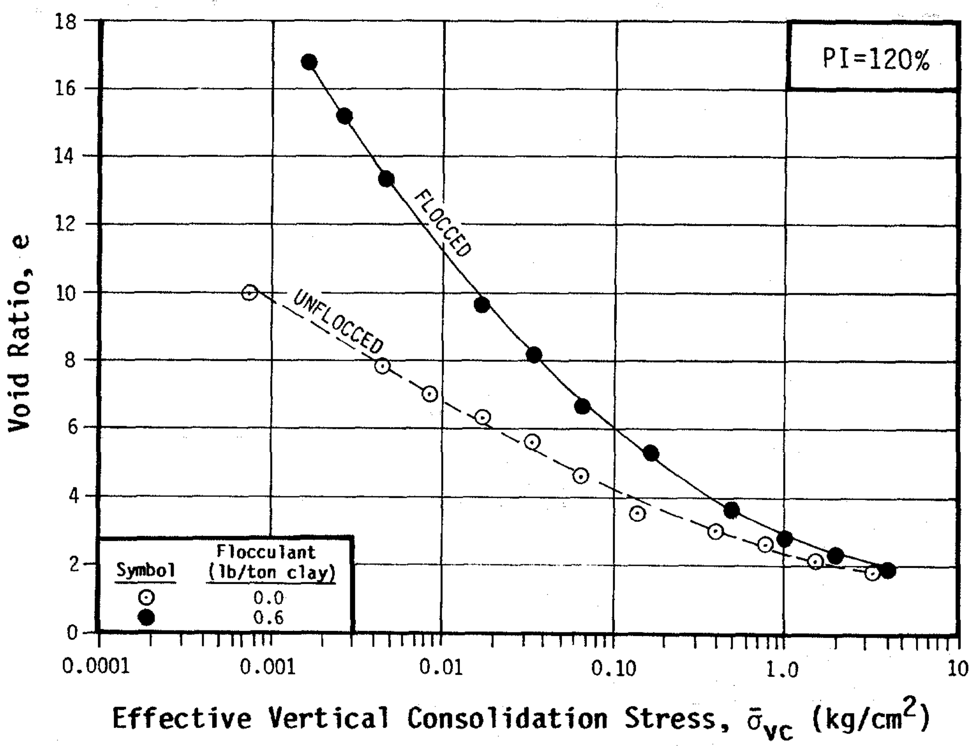
The coefficient of consolidation, c_v, of flocced and unflocced phosphatic clays at a given effective stress are similar for high plasticity clays. c_v is moderately higher for medium to low plasticity flocced clays than characteristic for unflocced clay. Somewhat higher coefficients of consolidation occur because the coefficients of permeability of the flocced clays at a given effective stress are greater than for unflocced clays. As a guide, average coefficients of consolidation in the range of $2x10^{-4}$ to $4x10^{-4}$ cm^2/sec should be typical for a wide range of flocced clays.

The coefficient of secondary compression of flocced phosphatic clays displayed no correlation with plasticity or monotonic trends with effective stress. As a general guideline, a coefficient of secondary compression for flocced clays of 1.4%±0.6% appears reasonable.



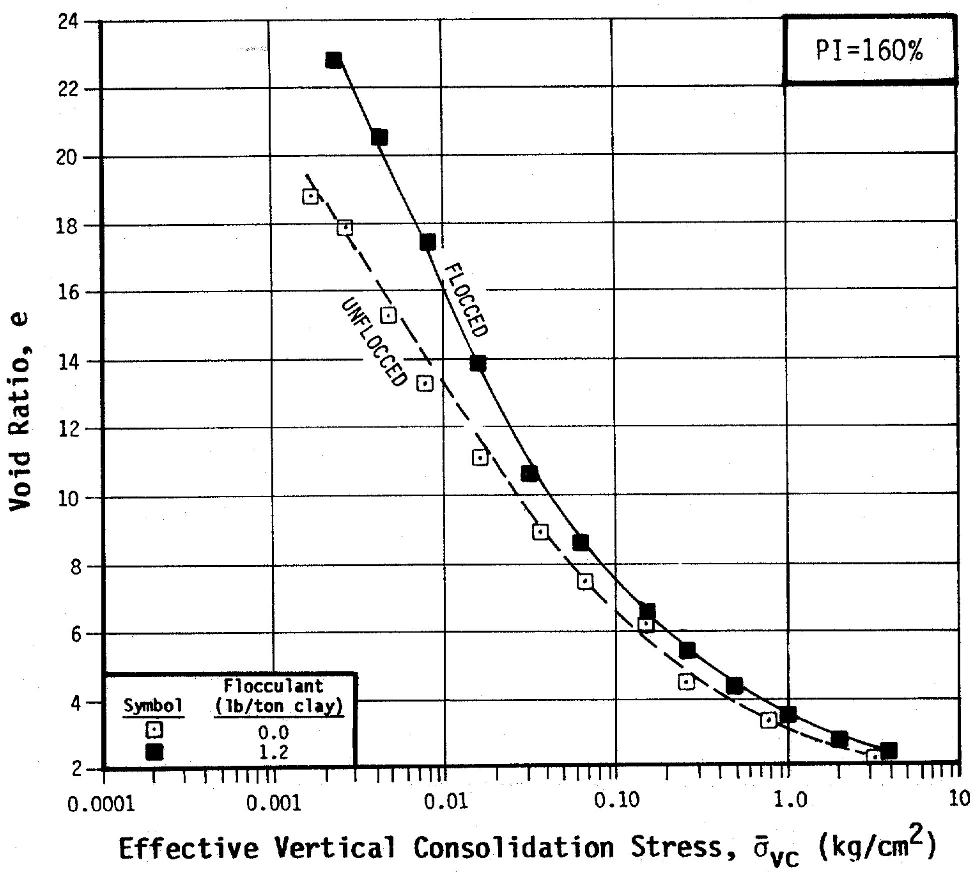
VOID RATIO VS. EFFECTIVE STRESS FOR AGRICO-SADDLE CREEK UNFLOCCED CLAY AND CLAY AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 4-1

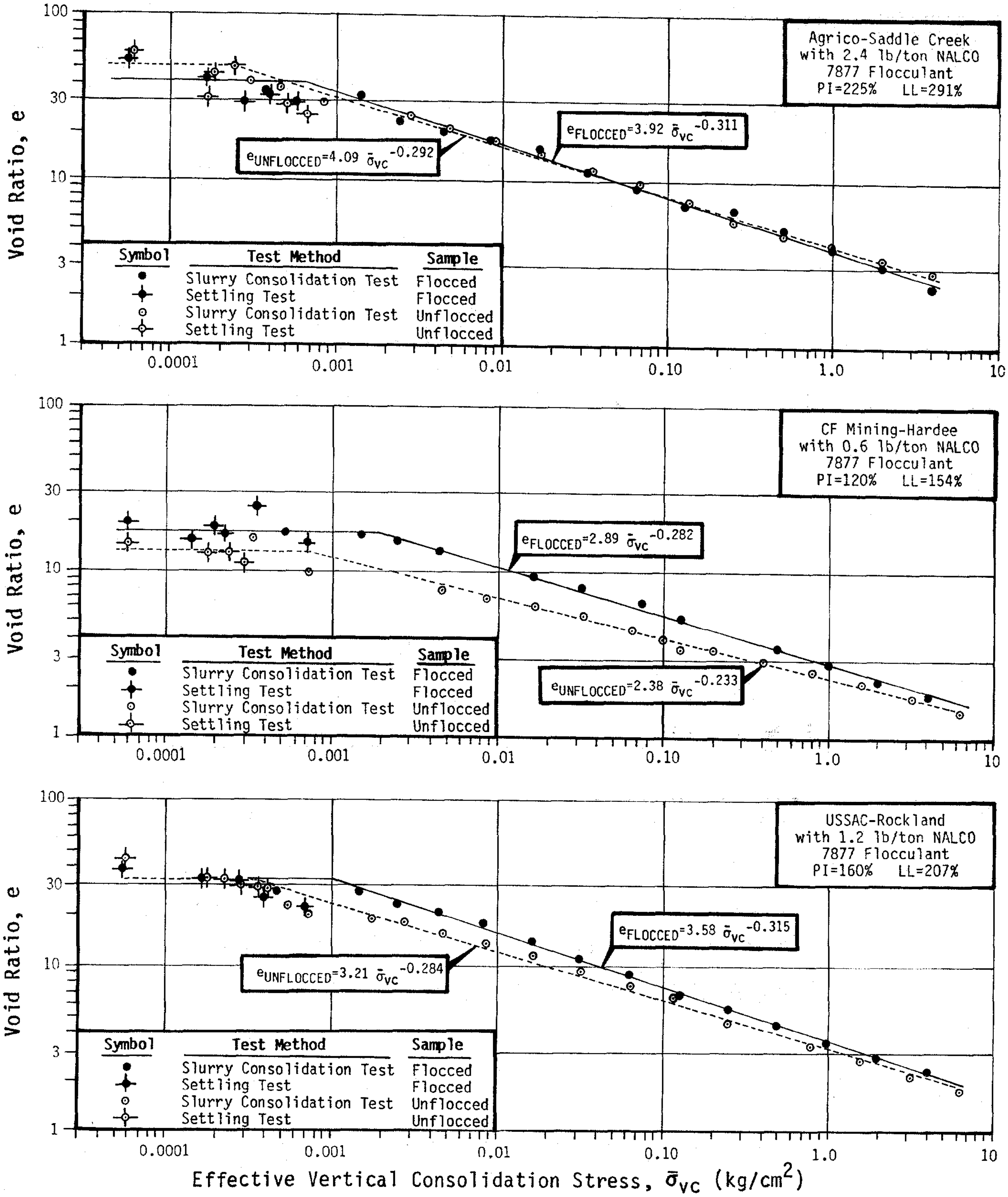


VOID RATIO VS. EFFECTIVE STRESS FOR CF MINING-HARDEE UNFLOCCED CLAY AND CLAY AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 4-2

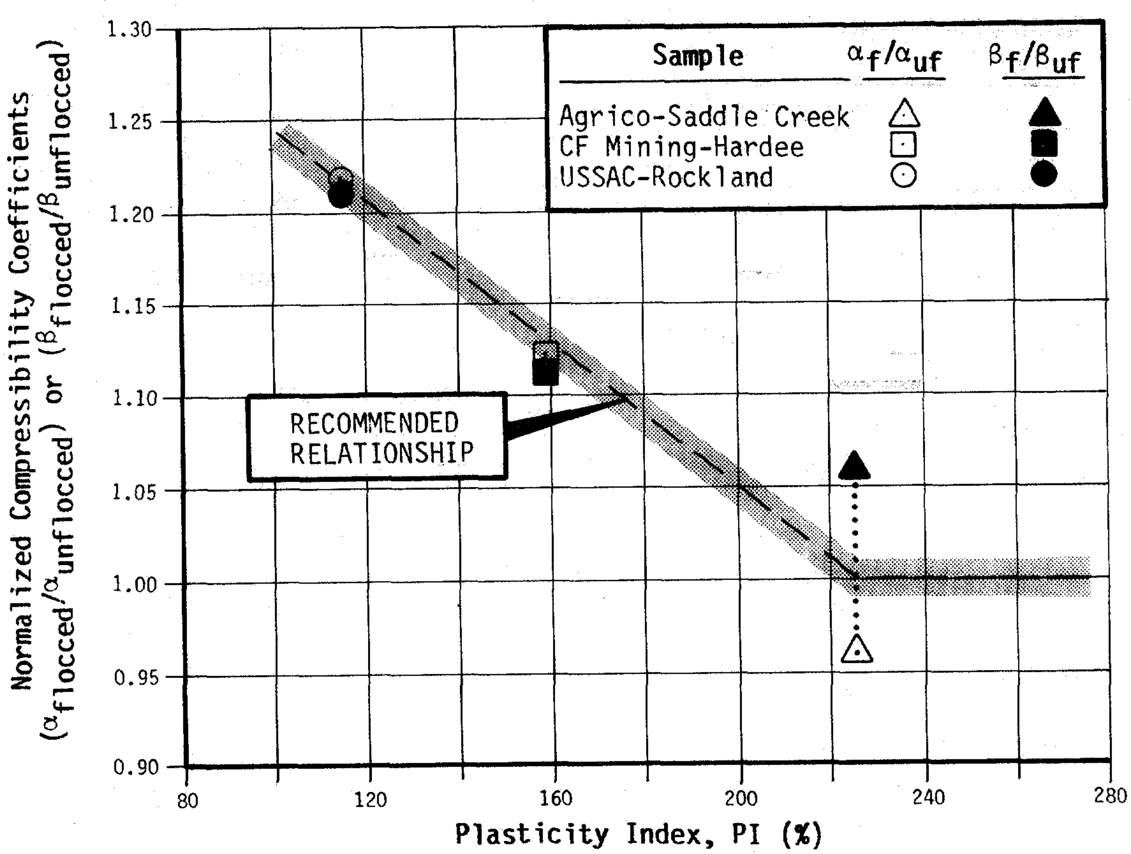


VOID RATIO VS. EFFECTIVE STRESS FOR USSAC-ROCKLAND UNFLOCCED CLAY AND CLAY AT OPTIMUM FLOCCULANT LOADING RATE



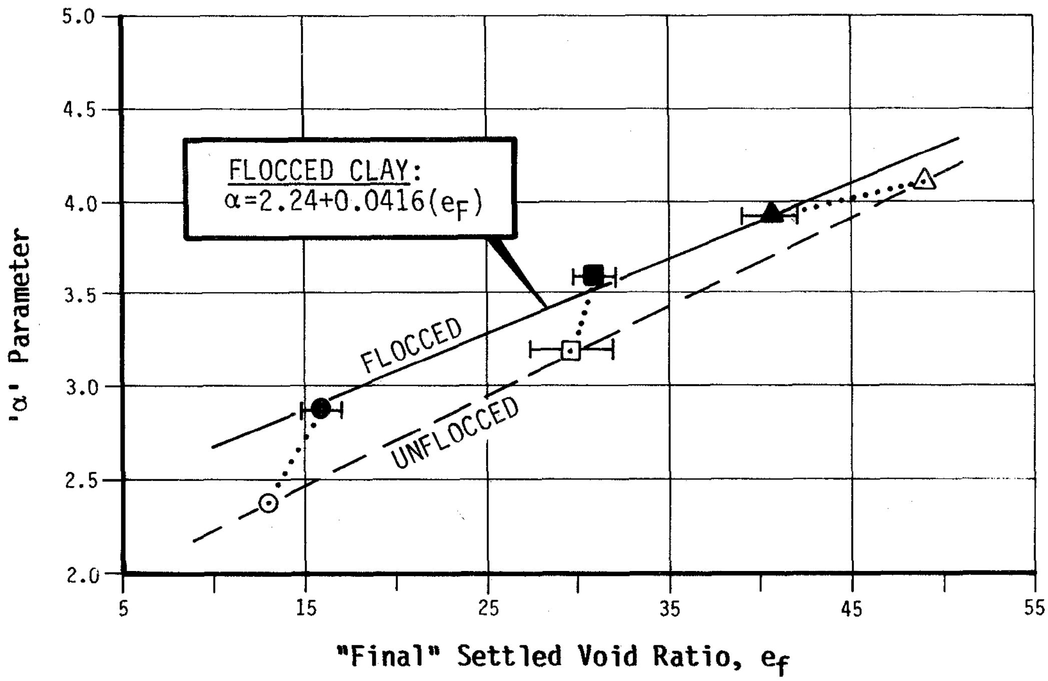
LOG VOID RATIO VS. LOG EFFECTIVE STRESS RELATIONSHIPS FOR UNFLOCCED CLAYS AND CLAYS AT OPTIMUM FLOCCULANT LOADING RATE

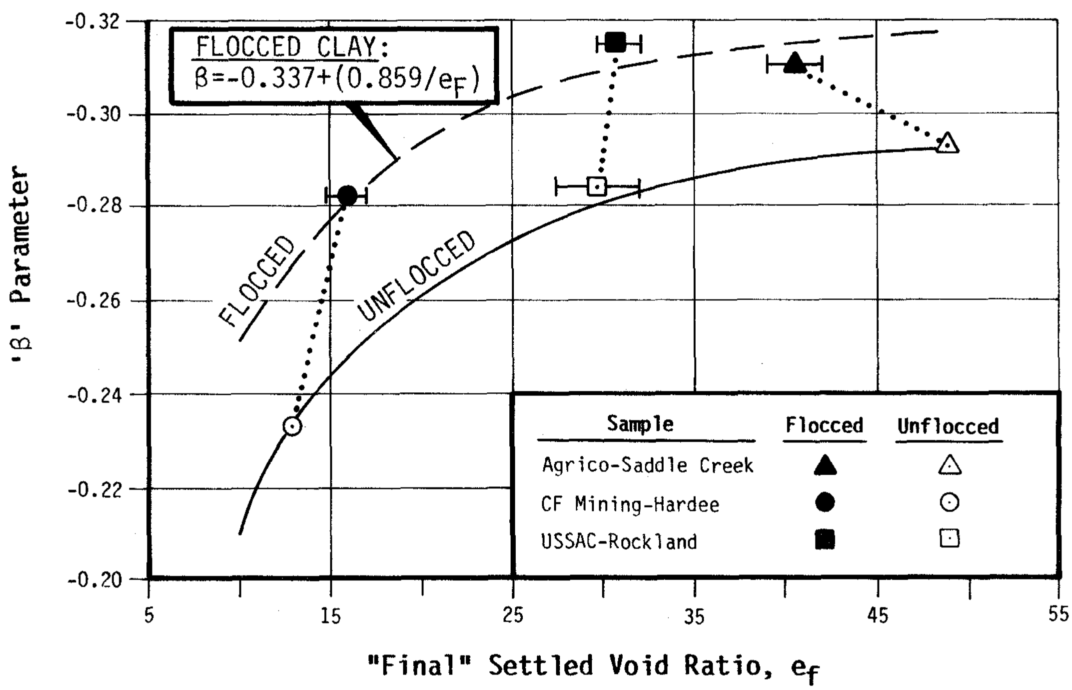
FIGURE 4-4



NORMALIZED COMPRESSIBILITY COEFFICIENTS VS. PLASTICITY INDEX FOR PHOSPHATIC CLAYS AT OPTIMUM FLOCCULANT LOADING RATE

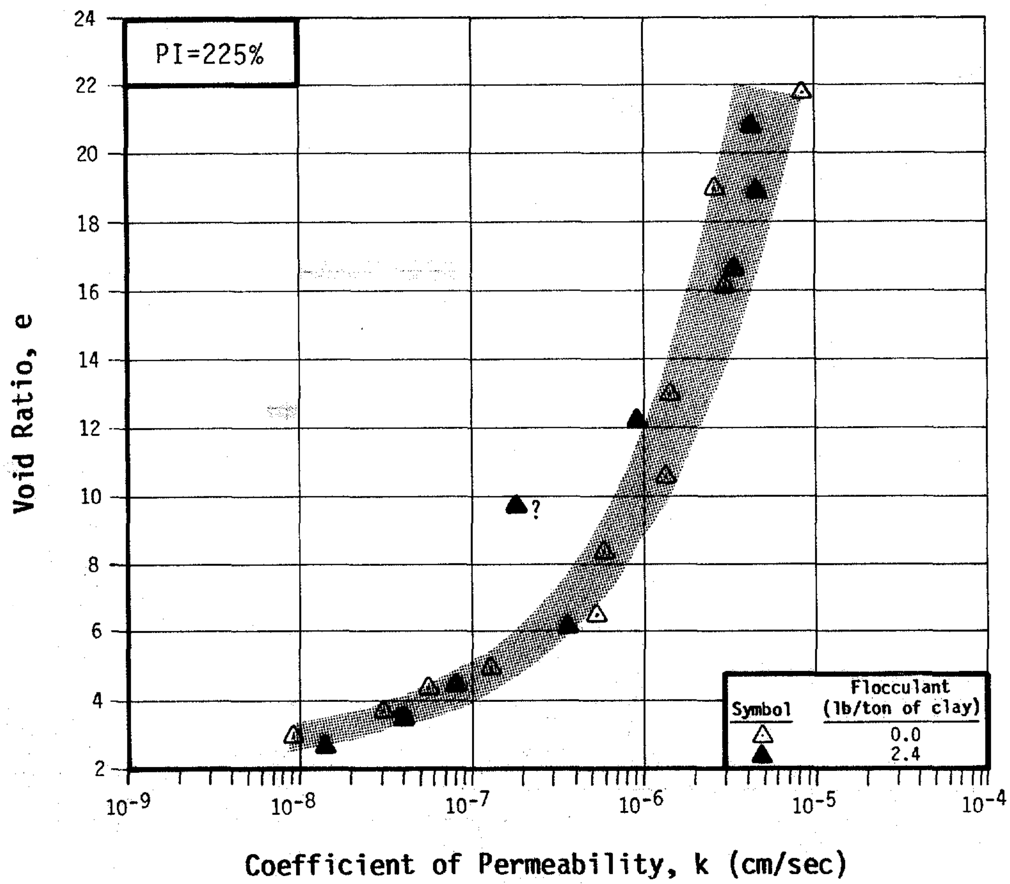
FIGURE 4-5





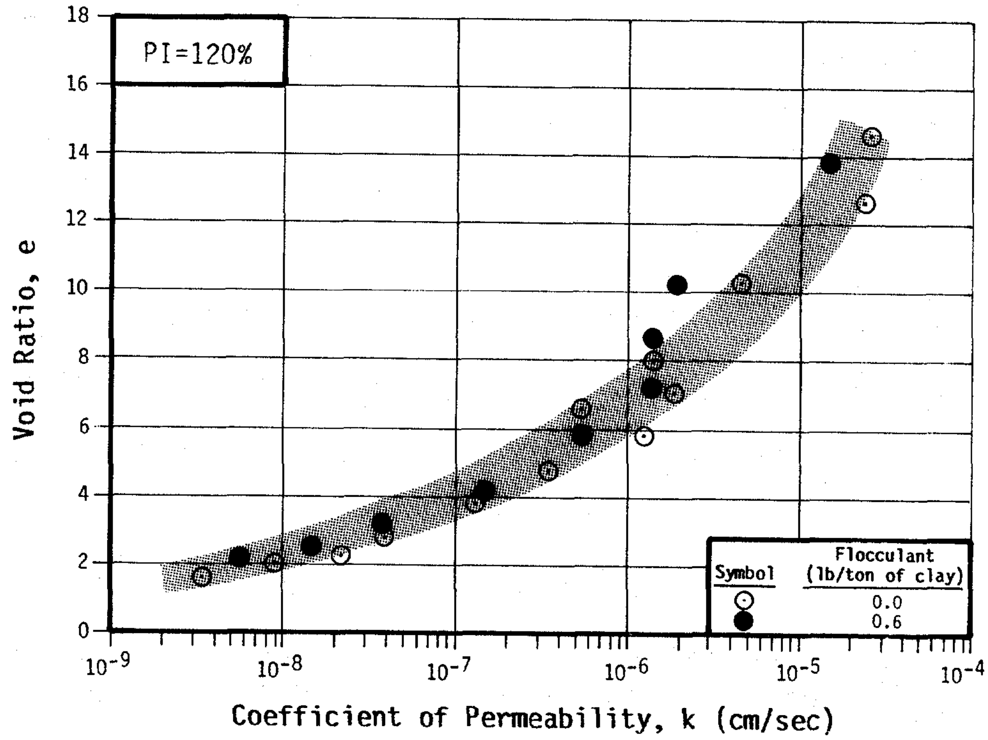
CORRELATION BETWEEN VOID RATIO FROM SETTLING TESTS AND α AND β COMPRESSIBILITY PARAMETERS FOR PHOSPHATIC CLAYS AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 4-6



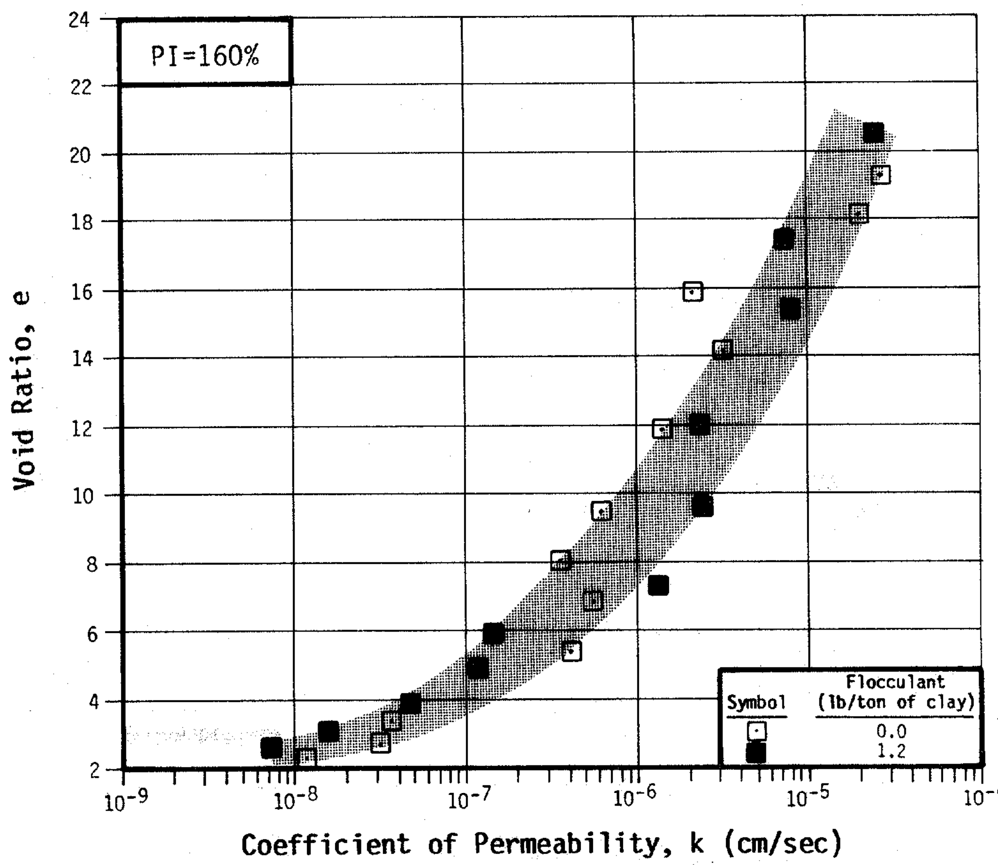
VOID RATIO VS. COEFFICIENT OF PERMEABILITY FOR AGRICO-SADDLE CREEK UNFLOCCED CLAY AND CLAY AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 4-7



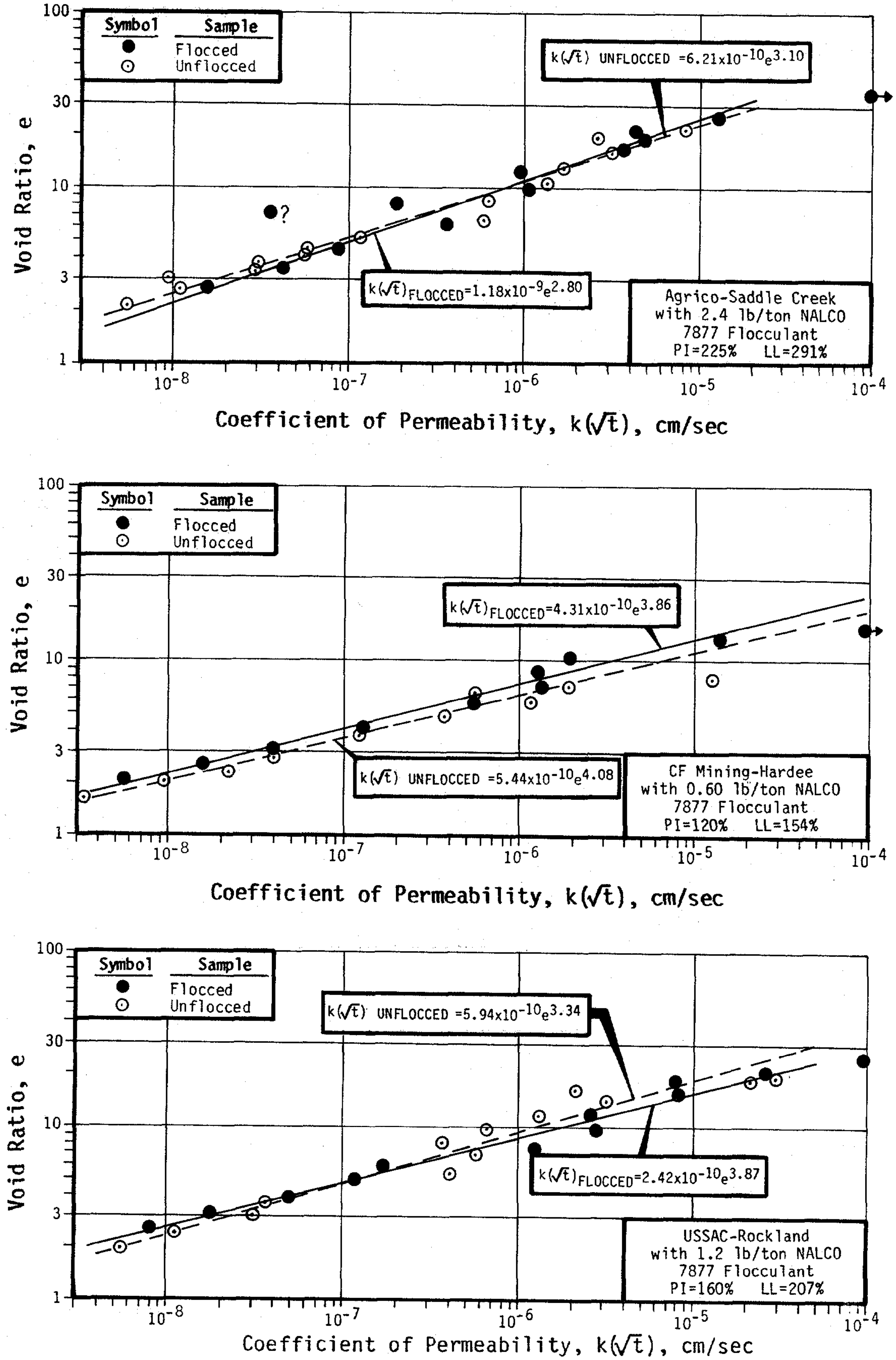
VOID RATIO VS. COEFFICIENT OF PERMEABILITY FOR CF MINING-HARDEE UNFLOCCED CLAY AND CLAY AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 4-8



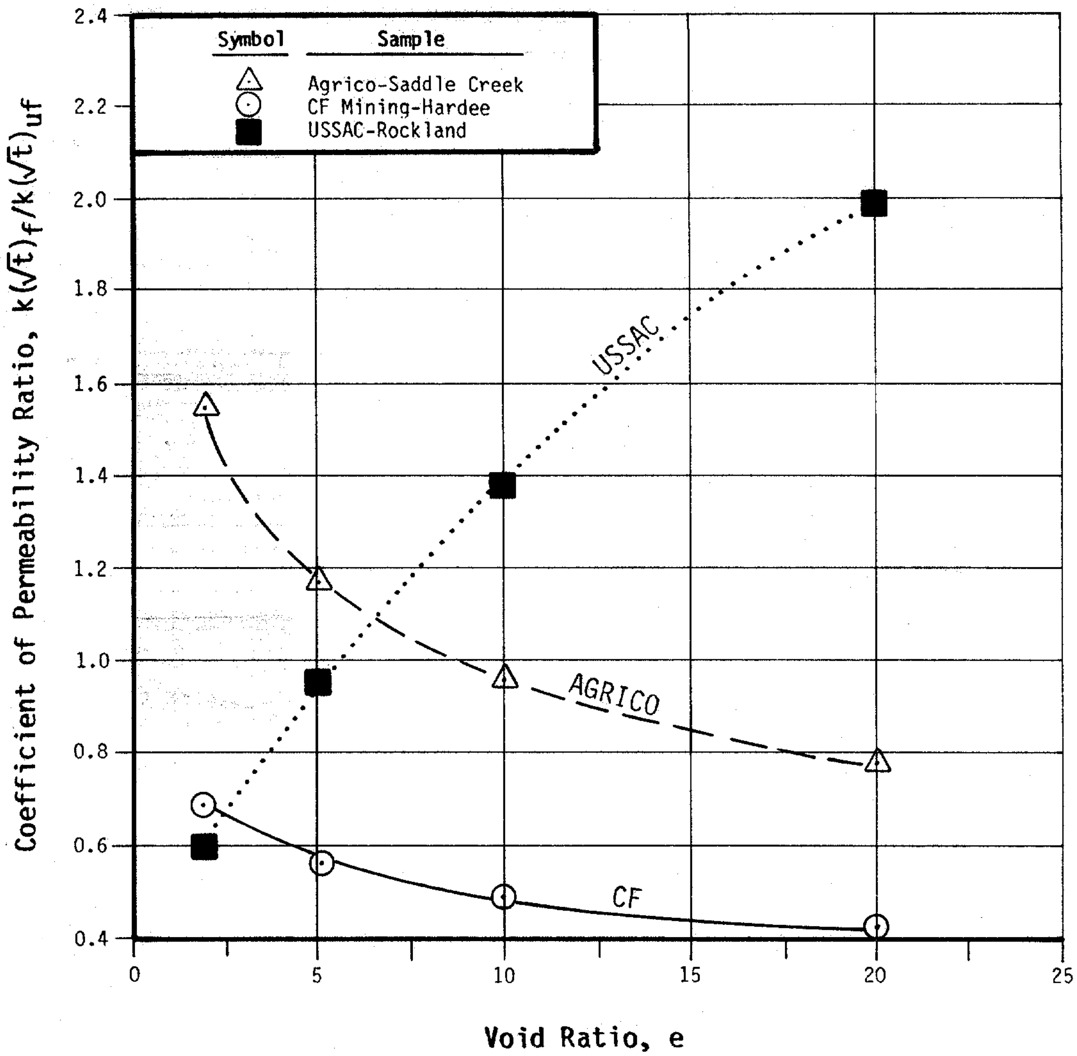
VOID RATIO VS. COEFFICIENT OF PERMEABILITY FOR USSAC-ROCKLAND UNFLOCCED CLAY AND CLAY AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 4-9



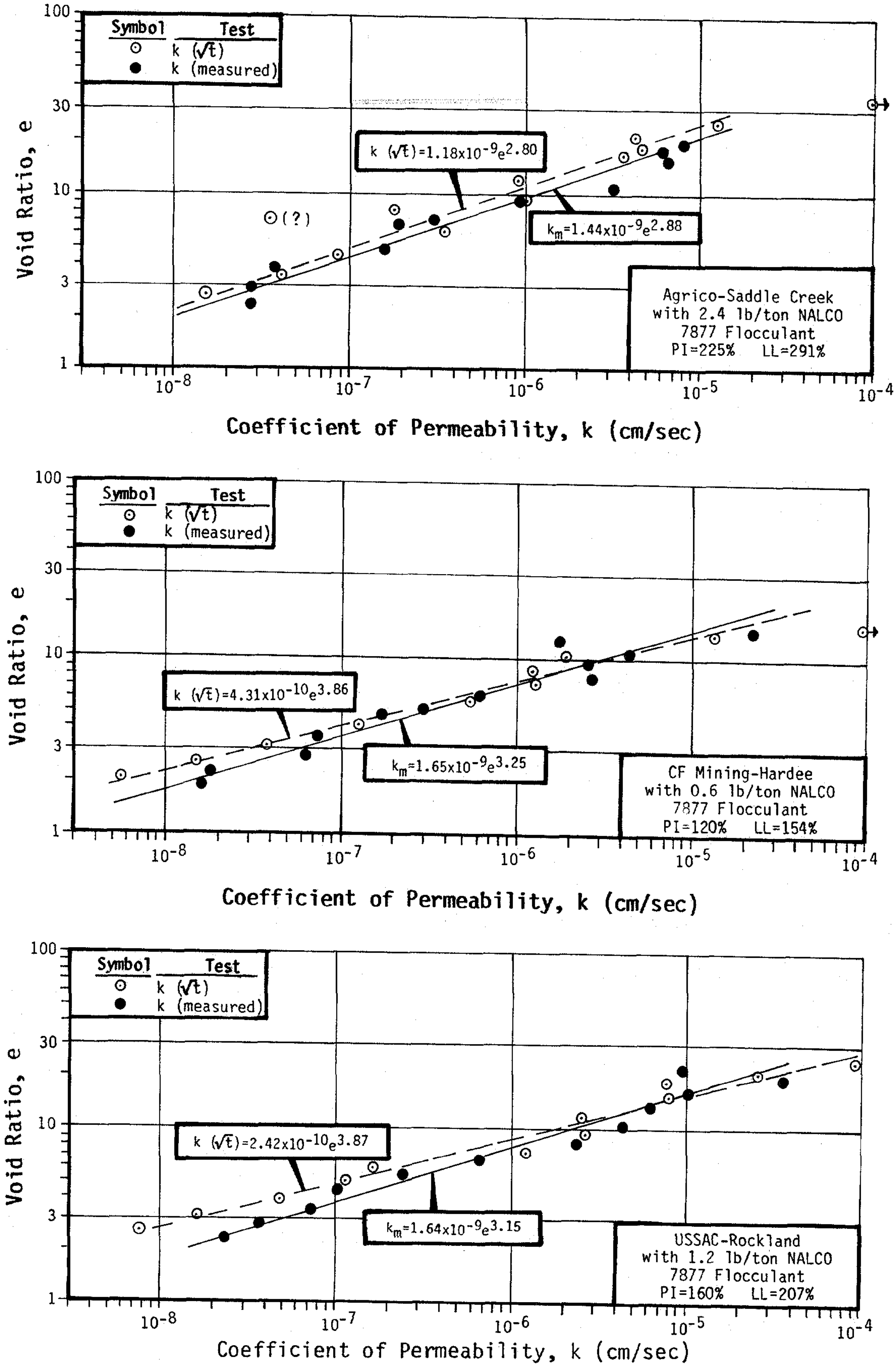
LOG VOID RATIO VS LOG COEFFICIENT OF PERMEABILITY RELATIONSHIPS FOR UNFLOCCED CLAYS AND CLAYS AT OPTIMUM UPTIMUM FLOCCULANT LOADING RATE

FIGURE 4-10



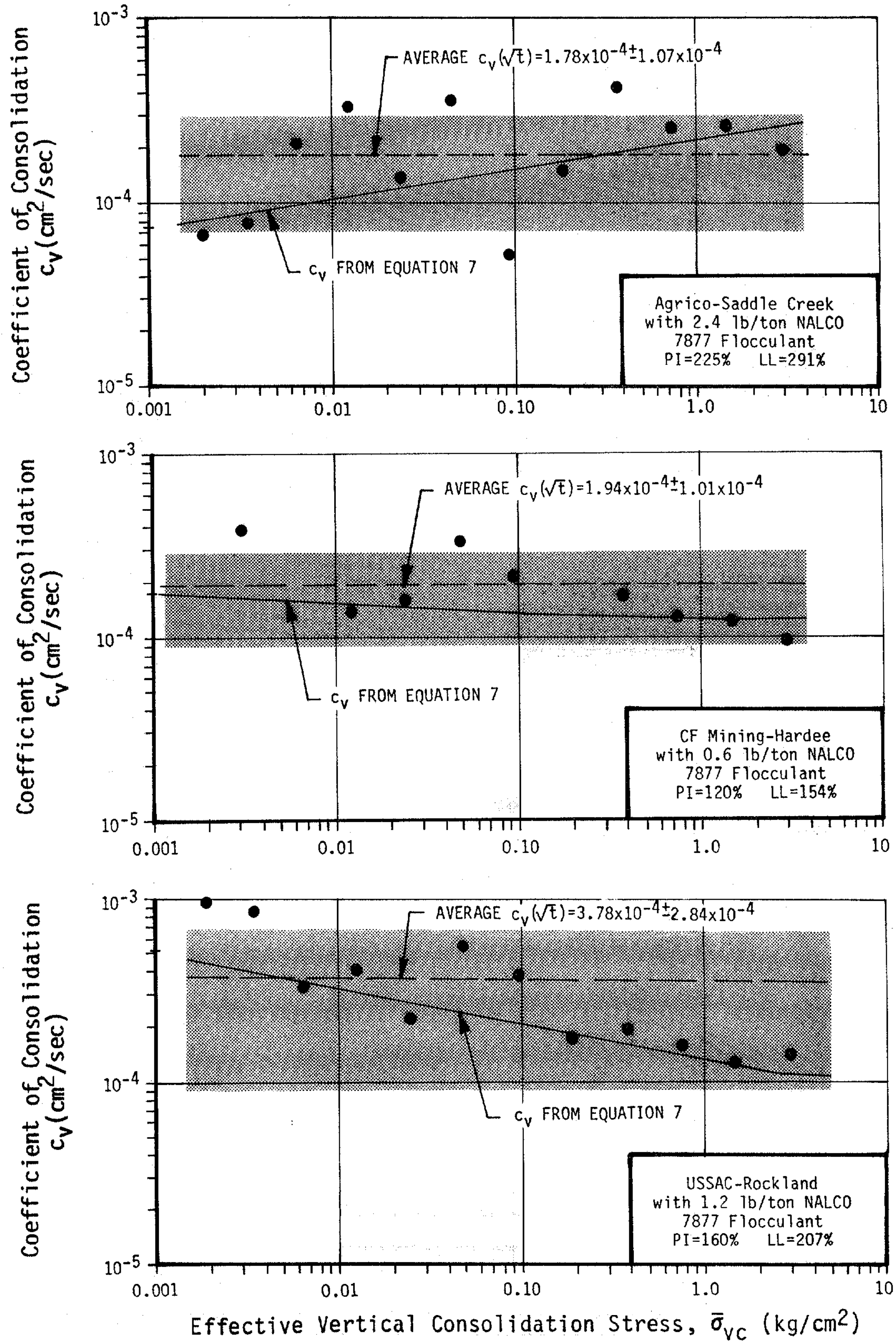
VOID RATIO VS COEFFICIENT OF PERMEABILITY RATIO FOR PHOSPHATIC CLAYS AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 4-11



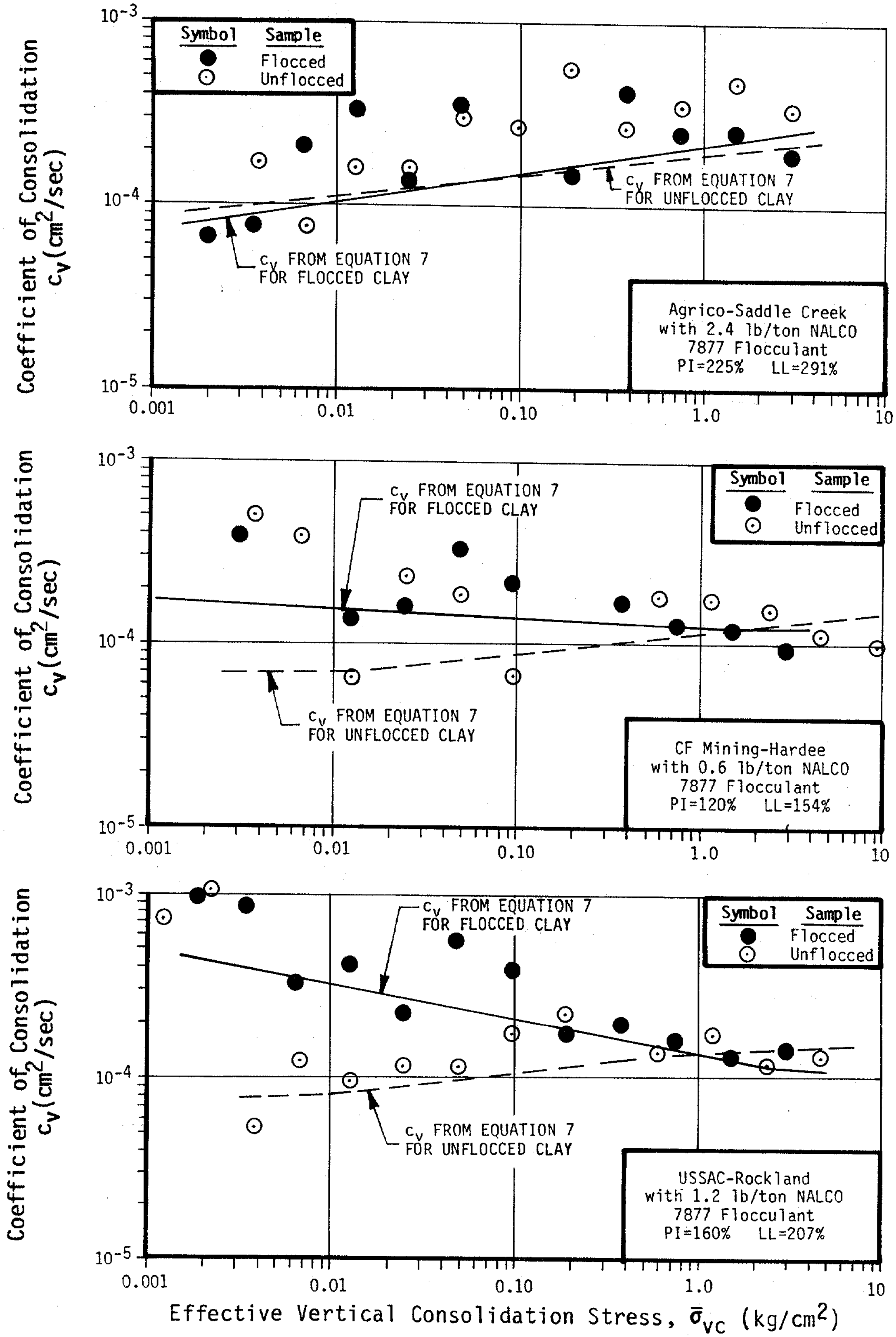
COMPARISON OF CALCULATED AND MEASURED COEFFICIENT OF PERMEABILITY FOR PHOSPHATIC CLAYS AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 4-12



VARIATION IN COEFFICIENT OF CONSOLIDATION WITH EFFECTIVE STRESS FOR PHOSPHATIC CLAYS AT OPTIMUM FLOCCULANT LOADING RATE

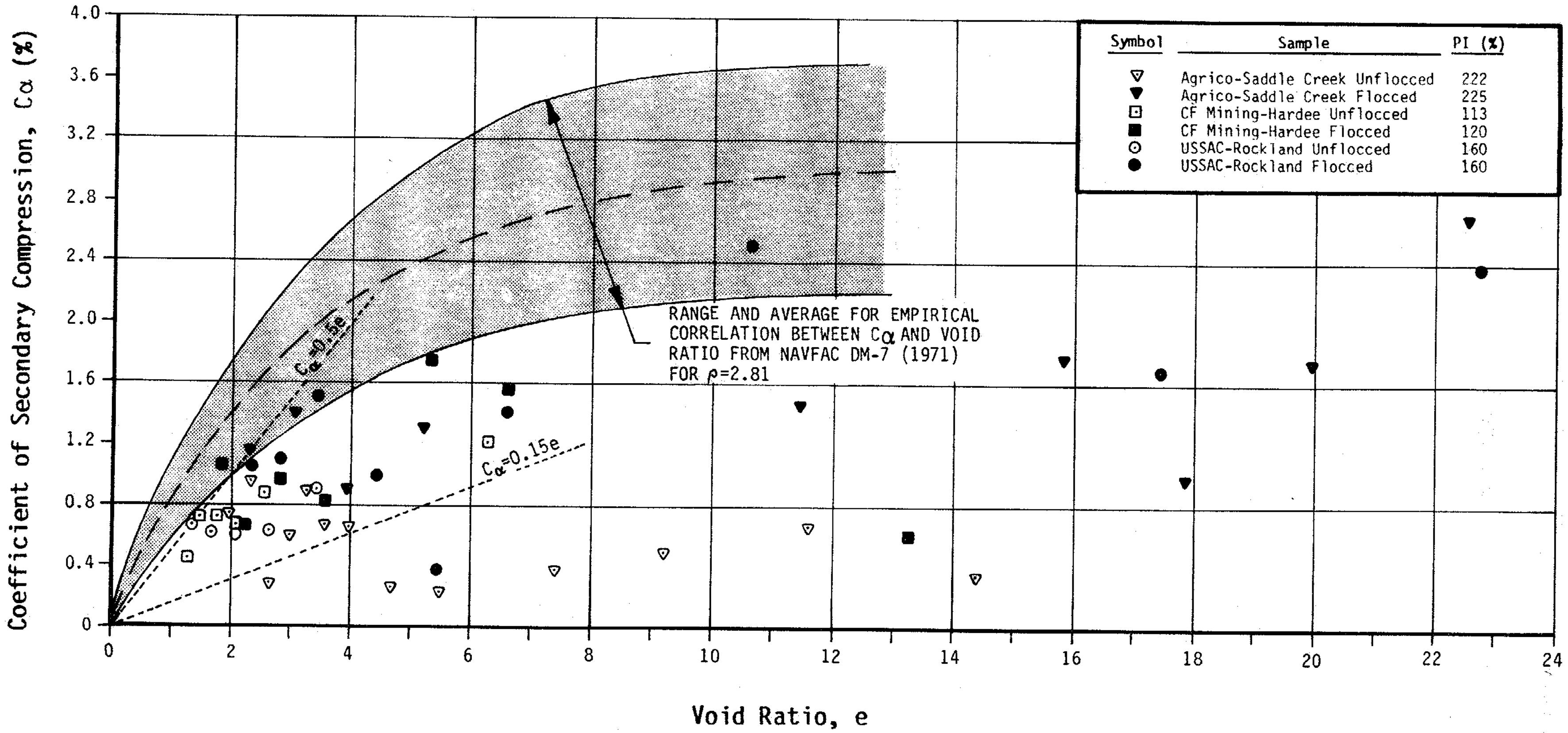
FIGURE 4-13



VARIATION IN COEFFICIENT OF CONSOLIDATION WITH EFFECTIVE STRESS FOR UNFLOCCED CLAYS AND CLAYS AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 4-14

FIGURE 4-15



VOID RATIO VS. COEFFICIENT OF SECONDARY COMPRESSION FOR UNFLOCCED CLAY AND CLAY AT OPTIMUM FLOCCULANT LOADING RATE

Section 5

SHEAR STRENGTH CHARACTERISTICS OF FLOCCULATED PHOSPHATIC CLAYS

5.1 Introduction

Three phosphatic clays representative of the range in plasticity determined on clay samples obtained from twelve different mine sites were flocced with NALCO 7877 flocculant to determine the effect of flocculation on the undrained stress-strain-strength behavior of phosphatic clays. As discussed in Section 1, the phosphatic clays selected for investigation were obtained from the Agrico-Saddle Creek mine (PI = 222%), the USSAC-Rockland mine (PI = 160%), and the CF Mining-Hardee mine (PI = 113%). These three clays are representative of relatively high, average and low plasticity phosphatic clays, respectively, and should indicate the effect of flocculation on the shear strength characteristics of a wide range of phosphatic clays.

5.2 Test Methods and Procedures

Two isotropically consolidated triaxial compression undrained shear tests with pore pressure measurement ($\overline{CIU}C$ tests) were performed on each of the selected phosphatic clay samples. After preparing the clay samples to an initial solids content of 3%, the clay slurries were flocced with NALCO 7877 flocculant in a 0.10% solution by volume added in one increment to produce the "optimum" flocculant loading rates of 2.4, 0.6 and 1.2 lb/ton of clay for the Agrico, CF and USSAC clays, respectively. The suspension was then slowly "stroked" with a perforated plunger-type stirrer until the maximum effect of the flocculant was observed. The stirrer was then removed and the height of interface with time was monitored. When no additional settling of the interface was observed the clear supernatant was drained and the settled suspension was poured into a large consolidometer.

K_o-consolidation of the settled suspensions was then performed in the laboratory using one load increment of about 0.4 kg/cm^2 applied via a special consolidometer to produce samples that permitted handling and trimming. The consolidometer used produced block samples of 10.2 cm in diameter and 12 cm in height. Triaxial test specimens were then trimmed from these larger samples to standard triaxial dimensions of 8.0 cm in height and approximately 3.6 cm in diameter.

The $\overline{CIU}C$ tests were conducted in accordance with the testing procedures previously outlined in Volume 5, Section 2.2.1. Two $\overline{CIU}C$ tests were performed at varying effective isotropic consolidation pressures, $\bar{\sigma}_c$, on each of the three flocculated phosphatic clays. The isotropic pre-shear effective consolidation pressures ranged from 0.5 to 1.5 kg/cm^2. Hence, the samples were consolidated prior to shear to effective stresses that were 1.25 to 3.75 times the maximum vertical effective stress used during sample preparation. All test samples were, therefore, normally consolidated. Various isotropic consolidation stresses, $\bar{\sigma}_c$, were used to confirm that flocced phosphatic clays exhibited normalized behavior and to determine the applicability of the Normalized Soil Parameter (NSP) concept to phosphatic clays (see Ladd and Foott, 1974). A clay exhibiting normalized behavior will yield values of normalized undrained shear strength, $s_u/\bar{\sigma}_c$, and normalized modulus, E_u/s_u, that are constant for samples consolidated to differing effective stresses in excess of the maximum past pressure.

5.3 Effect of Flocculation on Undrained Properties of Normally Consolidated Phosphatic Clays

5.3.1 Stress-Strain Behavior

Undrained effective stress paths and normalized stress-strain behavior from $\overline{\text{CIU}}$C tests on the flocced clays are presented in Figures 5-1 through 5-6. Undrained effective stress paths and normalized undrained stress-strain behavior from representative $\overline{\text{CIU}}$C tests on unflocced clay previously presented in Volume 5, Section 2.2, are also included for comparison. As shown, the undrained effective stress paths for the flocced and unflocced clays are similar exhibiting positive excess pore pressures during shear, a pore pressure A-factor at "failure", i.e., at maximum principal stress difference $(\sigma_1-\sigma_3)$max, of about 1.0 with the more plastic Agrico-Saddle Creek clay exhibiting an A-factor on the order of 1.2. The stress paths of both the flocced and unflocced clays are typical of those characteristic of normally consolidated soft clays.

The undrained normalized stress-strain behavior for the flocced and unflocced clays are also similar. The stress-strain curves are typical of normally consolidated soft clays with the maximum stress difference generally occurring at failure strains ranging from about 5% to 12%. Hence, flocculation does not appear to have a significant effect on the stress path or stress-strain behavior of phosphatic clays. Further, the effective stress paths and the stress-strain and pore pressure behavior support the applicability of the normalized soil parameter (NSP) concept to flocced phosphatic clays.

5.3.2 Undrained Shear Strength

The normalized undrained shear strength ratio, $s_u/\bar{\sigma}_c$, of the flocced and unflocced clays were generally similar with values ranging from 0.28 to 0.33 as shown in the lower graph of Figure 5-7 and as presented below. (The undrained shear strength, s_u, is defined herein as half the maximum principal stress difference, q, at failure; i.e., $s_u = q_f = 0.5(\sigma_1-\sigma_3)_{max}$; $\bar{\sigma}_c$ is the isotropic pre-shear effective consolidation stress.)

Sample	$s_u/\bar{\sigma}_c$ Unflocced	$s_u/\bar{\sigma}_c$ Flocced
Agrico-Saddle Creek	0.28	0.28
CF Mining-Hardee	0.33	0.29
USSAC-Rockland	0.30	0.31
Average	0.30	0.29

The undrained shear strength ratio normalized with respect to the one-dimensional vertical effective consolidation stress, $\bar{\sigma}_{vc}$, rather than the isotropic stress, $\bar{\sigma}_c$, may be backfigured from $\overline{CIUC}$ tests by assuming that the flocced phosphatic clays exhibit basic strength principles in accordance with the "simple clay model" (Ladd, 1964). In accordance with this hypothesis and using a coefficient of earth pressure at rest K_o = 0.6, $s_u/\bar{\sigma}_{vc}$ may be directly determined from the effective stress paths presented in Figures 5-1 through 5-3. The resulting values of $s_u/\bar{\sigma}_{vc}$ calculated for each phosphatic clay are presented in the upper graph of Figure 5-7 and summarized below:

Sample	$s_u/\bar{\sigma}_{vc}$	
	Unflocced	Flocced
Agrico-Saddle Creek	0.26	0.29
CF Mining-Hardee	0.29	0.27
USSAC-Rockland	0.28	0.27
Average	0.28	0.28

As shown, the resulting $s_u/\bar{\sigma}_{vc}$ values for the flocced and unflocced clays are generally similar, ranging from 0.26 to 0.29, and as expected are less than the corresponding measured $s_u/\bar{\sigma}_c$ values. Overall, the flocced and unflocced clays exhibit an average $s_u/\bar{\sigma}_{vc}$ ratio of 0.28 irrespective of plasticity and flocculant loading rate.

Although the $s_u/\bar{\sigma}_c$ and $s_u/\bar{\sigma}_{vc}$ ratios for flocced and unflocced clays are generally similar, a small effect of flocculation on the normalized undrained shear strength ratio exists as shown in Figure 5-8. The relatively low plasticity CF clay displays $s_u/\bar{\sigma}_c$ and $s_u/\bar{\sigma}_{vc}$ ratios for flocced clay about 10% less than for unflocced clay. Conversely, the relatively high plasticity Agrico flocced clay displays $s_u/\bar{\sigma}_c$ and $s_u/\bar{\sigma}_{vc}$ ratios about 5% greater than unflocced clay. Accordingly, flocculation appears to increase slightly the undrained shear strength of the high plasticity phosphatic clays and decrease slightly the undrained shear strength of the low plasticity phosphatic clays! This relatively weak trend, however, is strictly applicable for NALCO 7877 flocculant at the specified loading rate added to the clay in one increment in accordance with the described test methods.

Since $s_u/\bar{\sigma}_{vc}$ is similar for flocced and unflocced phosphatic clays, an average value $s_u/\bar{\sigma}_{vc}$ = 0.28 may be used for other phosphatic clays in the absence of laboratory test data. This value is characteristic of the shear strength in compression, s_u(V), when the clay is sheared with the major principal stress in the vertical direction. The normalized undrained shear strength ratio of 0.28 is slightly higher than expected for the highly plastic phosphatic clays. Volume 5 discusses recommended shear strength properties for phosphatic clays which should also be applicable for flocculated clays.

5.3.3 Undrained Modulus

The undrained modulus governs the magnitude of undrained deformations resulting from loading a phosphatic clay deposit. Values of Young's secant undrained modulus, E_u, are highly dependent on stress level.

Values of E_u/s_u (normalized secant modulus with respect to the undrained shear strength) from $\overline{CIUC}$ tests are presented in Figures 5-9 through 5-11 for each flocced clay as a function of stress level q/q_f (where q is the maximum shear stress for a particular loading, or half the principal stress difference; and q_f is the value of q at maximum stress difference $(\sigma_1-\sigma_3)_{max}$, i.e., at failure). For comparison, values of E_u/s_u versus stress level previously established for the unflocced clays are also included. As shown, no consistent effect of flocculation was observed. The Agrico flocced clay E_u/s_u values decreased at a given stress level, the CF flocced clay E_u/s_u values were similar and the USSAC flocced clay E_u/s_u vlaues increased at a given stress level. The trends, magnitudes and variability in E_u/s_u for the flocced clays are consistent, however, with the range and average previously found for other phosphatic clays as discussed in Volume 5, Section 2.2.5. Overall, considering the variability in the data the average E_u/s_u curve shown for the unflocced clays also appears reasonable for the flocced clays.

5.3.4 Angle of Internal Friction

The effective angle of internal friction, $\bar{\phi}$, is required for evaluating the drained class of stability problems which are performed to assess long-term stability when consolidation due to loading (or unloading) of a clay deposit has been completed. This class of stability problems can be important but, in conjunction with construction on a soft phosphatic clay deposit where the undrained case governs, the angle of friction is generally not as important as the undrained shear strength.

The effective angle of internal friction, $\bar{\phi}$, of each flocced clay was determined from $\overline{CIUC}$ tests at maximum obliquity, maximum stress difference, and tangency to the effective stress paths. Figures 5-1, 5-2 and 5-3 illustrate the Mohr-Coulomb failure envelopes (K_F lines) drawn tangent to the effective stress paths for each clay. As shown, both the flocced and unflocced clays are characterized by zero effective cohesion ($\bar{c}$=0) and an angle of internal friction, $\bar{\phi}$, of 30° for a failure envelope tangent to the effective stress paths. The average values and ranges in $\bar{\phi}$ determined at maximum obliquity $(\bar{\sigma}_1/\bar{\sigma}_3)_{max}$ and at maximum stress difference $(\sigma_1-\sigma_3)_{max}$ are presented in Figure 5-12 and summarized below:

	$\bar{\phi}$ At $(\bar{\sigma}_1/\bar{\sigma}_3)_{max}$		$\bar{\phi}$ At $(\sigma_1-\sigma_3)_{max}$	
Sample	Unflocced	Flocced	Unflocced	Flocced
Agrico-Saddle Creek	31.1°	29.5°	29.6°	29.4°
CF Mining-Hardee	30.3°	27.8°	29.4°	25.9°
USSAC-Rockland	30.9°	28.3°	29.6°	26.4°
Average	30.8°	28.5°	28.6°	27.2°

As shown, the flocced clays display angles of internal friction equivalent to or slightly less than the unflocced clays for both the maximum obliquity and maximum stress difference failure criterion. Since the angles of internal friction are not significantly different, representative values of 28° at maximum obliquity and 27° at maximum stress difference can be used.

Ladd (1971) concluded that, for normally consolidated clays, the angle of internal friction under drained conditions, $\bar{\phi}_d$, is generally up to 3 degrees lower than $\bar{\phi}$ at maximum obliquity. Hence, in the absence of drained tests and on the basis of $\overline{\text{CIU}}$C tests, $\bar{\phi}_d$ of flocced phosphatic clays is anticipated to be on the order of 25°. This friction angle is much higher than expected for the highly plastic phosphatic clays based on correlations with plasticity presented in NAVFAC DM-7 (1971) wherein $\bar{\phi}_d$ is on the order of 20°. Hence, $\bar{\phi}_d$ probably lies between 20° and 25°. Accordingly, a drained effective friction angle, $\bar{\phi}_d$, of 23° is indicated for flocced clays for the drained class of stability problems.

5.4 **Summary and Practical Implications**

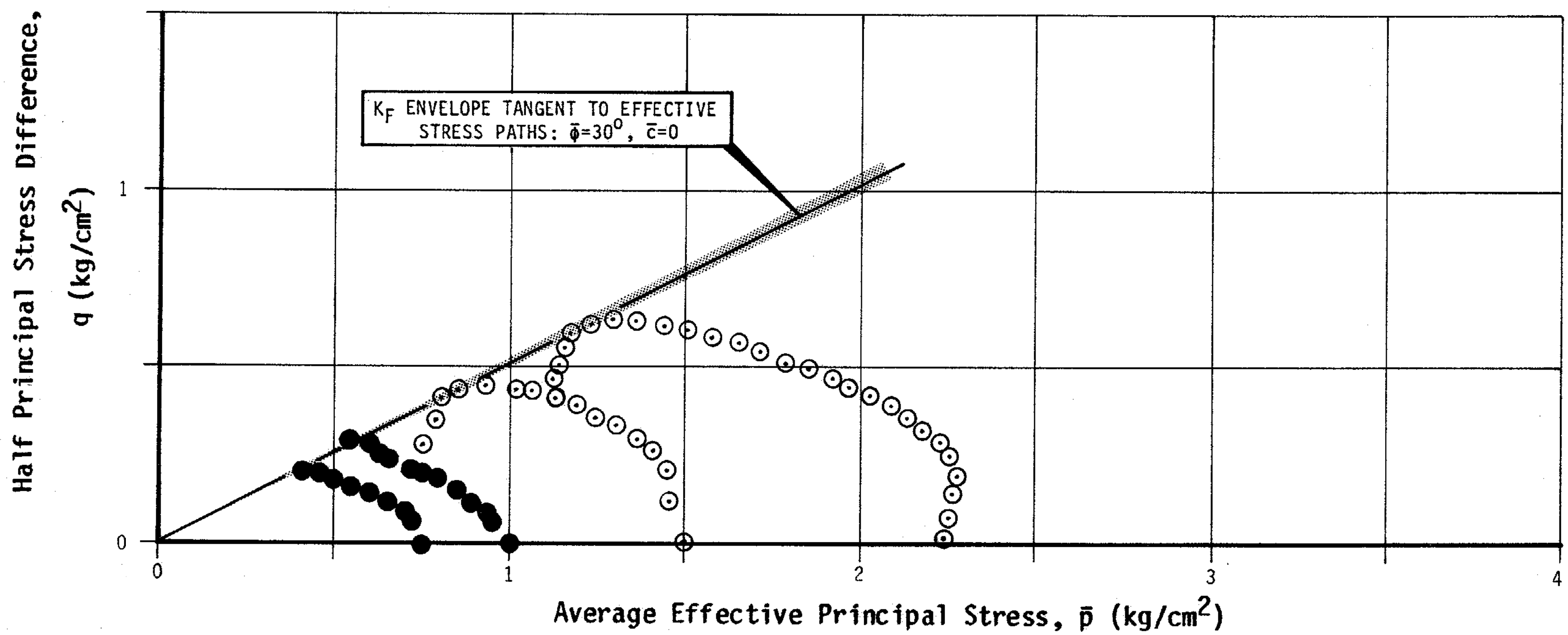
The results from $\overline{\text{CIU}}$C tests indicate that the undrained effective stress paths and stress-strain behavior of normally consolidated flocced and unflocced clays are similar. Hence, flocculation does not have a major effect on the stress-strain-strength behavior of phosphatic clays. Further, the effective stress paths and stress-strain behavior support the applicability of the normalized soil parameter concept to flocced phosphatic clays.

A very slight effect of flocculation on the normalized undrained shear strength ratio, $s_u/\bar{\sigma}_{vc}$, was noted for normally consolidated phosphatic clays. Overall, however, $s_u/\bar{\sigma}_{vc}$ from $\overline{\text{CIU}}$C tests appears similar for all flocced and unflocced clays with a representative gross average value of 0.28 being representative for normally consolidated phosphatic clays.

Effective angles of internal friction, $\bar{\phi}$, determined at maximum obliquity and at maximum stress difference for flocced and unflocced clays were not significantly different. For drained effective stress type stability analyses an effective angle of internal friction, $\bar{\phi}_d$, of 23° was found characteristic for normally consolidated flocced clays.

No consistent effects of flocculation on the normalized undrained Young's secant modulus were observed for the phosphatic clays.

Symbol	Sample	LL (%)	PI (%)	Specimen	Initial		Pre-Shear		$Su/\bar{\sigma}_c$	At $(\sigma_1-\sigma_3)$max			At $(\bar{\sigma}_1/\bar{\sigma}_3)$max		
					ω_n(%)	γ_t(pcf)	ω_n(%)	γ_t(pcf)		ξ(%)	$\bar{\phi}$ (°)	A Factor	ξ(%)	$\bar{\phi}$ (°)	A Factor
⊙	Unflocced Clay	268	222	S8 S9	190.1 205.1	77.7 76.9	109.4 130.6	90.0 86.5	0.27 0.29	6.9 6.7	28.2 29.5	1.28 1.14	10.9 10.6	29.8 31.1	1.42 1.26
●	Flocced Clay (2.4 lb/ton clay NALCO 7877)	291	225	S1 S2	246.2 247.3	73.6 73.3	164.9 189.6	82.2 80.1	0.29 0.27	9.5 14.9	29.4 29.4	1.27 1.34	- 16.7	- 29.5	- 1.35



UNDRAINED EFFECTIVE STRESS PATHS FROM $\overline{CIU}$C TESTS ON NORMALLY CONSOLIDATED AGRICO-SADDLE CREEK UNFLOCCED CLAY AND CLAY AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 5-1

Symbol	Sample	LL (%)	PI (%)	Specimen	Initial		Pre-Shear		$Su/\bar{\sigma}_c$	At$(\sigma_1-\sigma_3)$max			At$(\bar{\sigma}_1/\bar{\sigma}_3)$max		
					ω_n(%)	γ_t(pcf)	ω_n(%)	γ_t(pcf)		ϵ(%)	$\bar{\phi}$ (°)	A Factor	ϵ(%)	$\bar{\phi}$ (°)	A Factor
⊙	Unflocced Clay	143	113	S1 S3	111.5 113.4	90.1 91.3	86.6 116.4	95.4 88.9	0.32 0.34	5.7 7.4	28.6 29.3	1.03 0.92	9.6 9.5	28.8 29.9	1.17 0.97
●	Flocced Clay (0.6 lb/ton clay NALCO 7877)	154	118	S1 S2	130.4 128.8	80.8 80.8	113.8 94.0	89.4 48.2	0.30 0.29	8.8 9.9	24.5 27.2	1.03 1.12	18.1 18.8	26.3 29.2	1.14 1.27

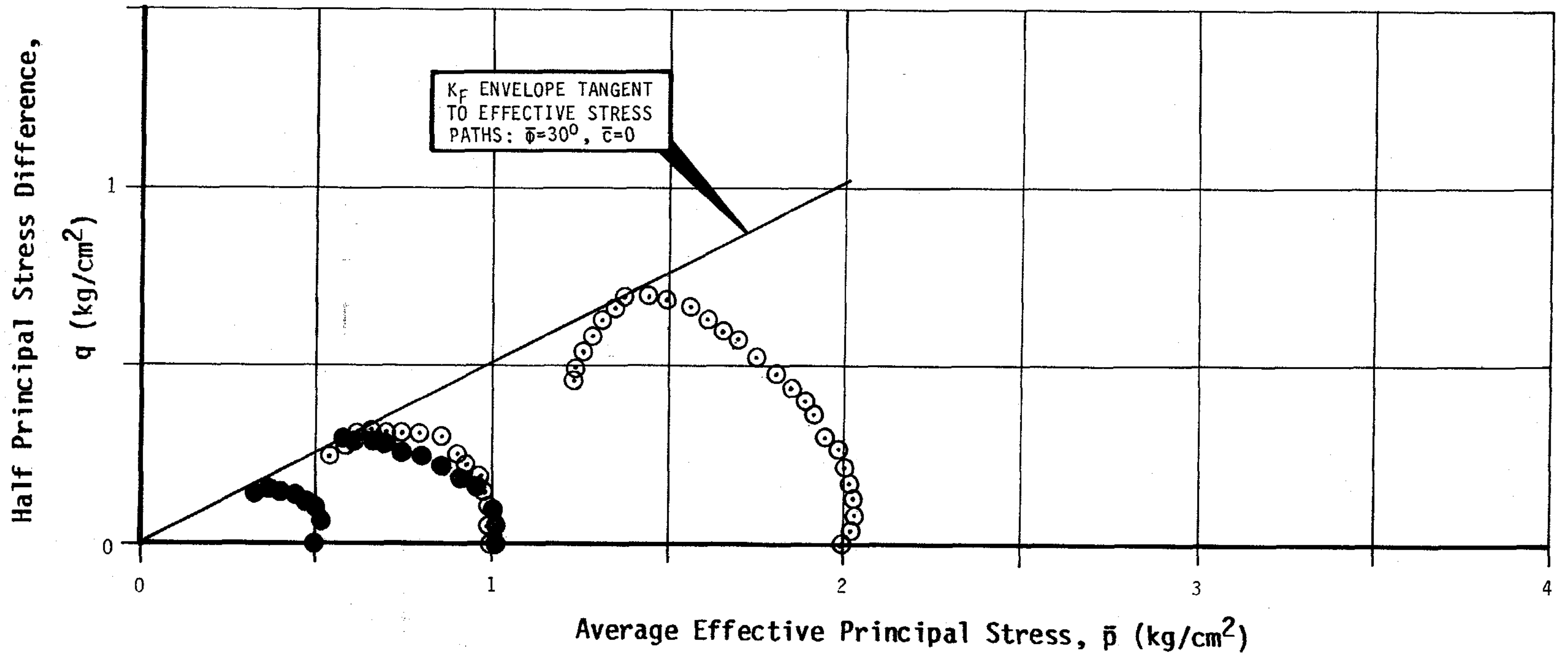


FIGURE 5-2

UNDRAINED EFFECTIVE STRESS PATHS FROM CIUC TESTS ON NORMALLY CONSOLIDATED CF MINING-HARDEE UNFLOCCED CLAY AND CLAY AT OPTIMUM FLOCCULANT LOADING RATE

Symbol	Sample	LL (%)	PI (%)	Specimen	Initial		Pre-Shear		$Su/\bar{\sigma}_c$	At$(\sigma_1-\sigma_3)$max			At$(\bar{\sigma}_1/\bar{\sigma}_3)$max		
					ω_n(%)	γ_t(pcf)	ω_n(%)	γ_t(pcf)		ξ(%)	$\bar{\phi}$ (°)	A Factor	ξ(%)	$\bar{\phi}$ (°)	A Factor
⊙	Unflocced Clay	195	160	S1 S4	143.4 139.6	85.2 85.5	110.0 91.3	90.1 94.1	0.33 0.28	8.4 8.9	32.4 26.8	1.05 1.23	12.8 9.4	34.8 26.8	1.16 1.26
●	Flocced Clay (1.2 lb/ton clay NALCO 7877)	207	158	S1 S2	172.5 170.1	77.5 77.2	133.6 160.6	85.9 82.7	0.27 0.36	5.5 5.3	25.0 27.9	1.16 0.90	9.9 7.9	26.1 30.4	1.35 1.00

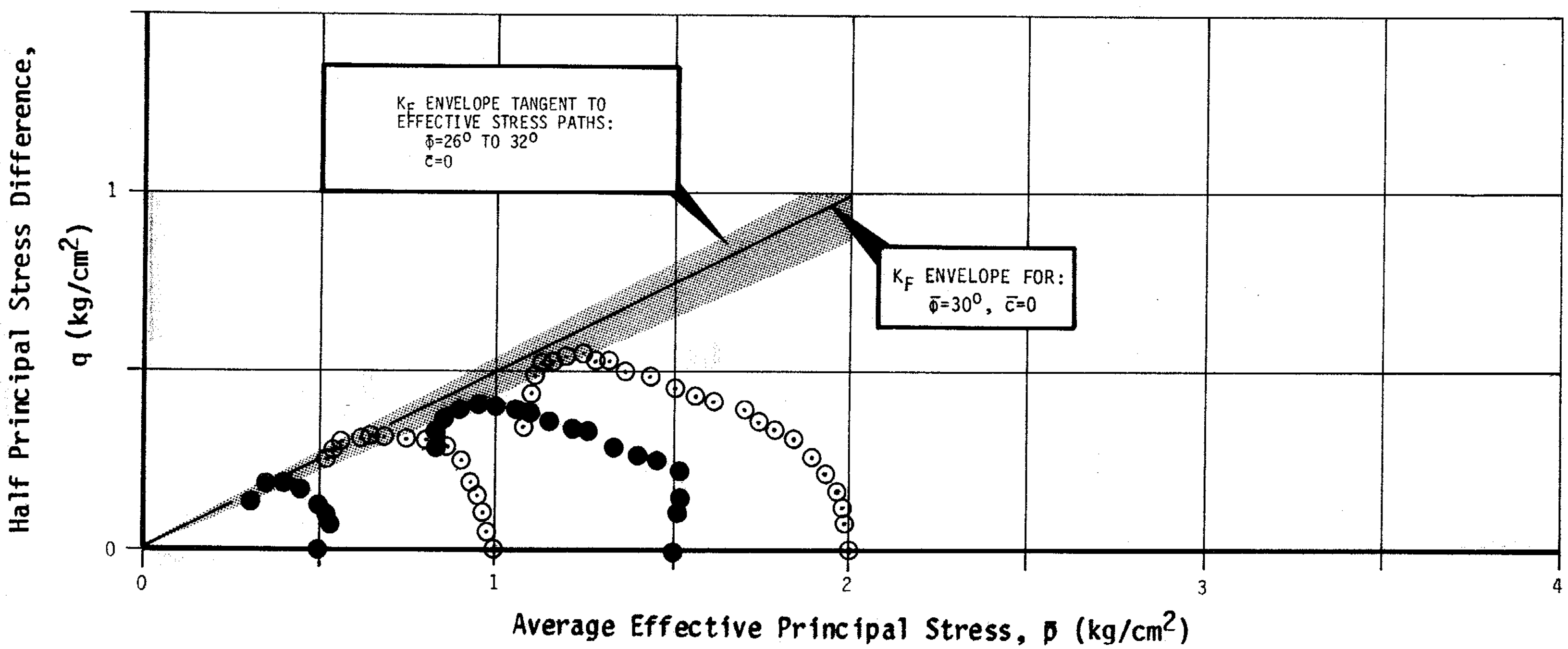
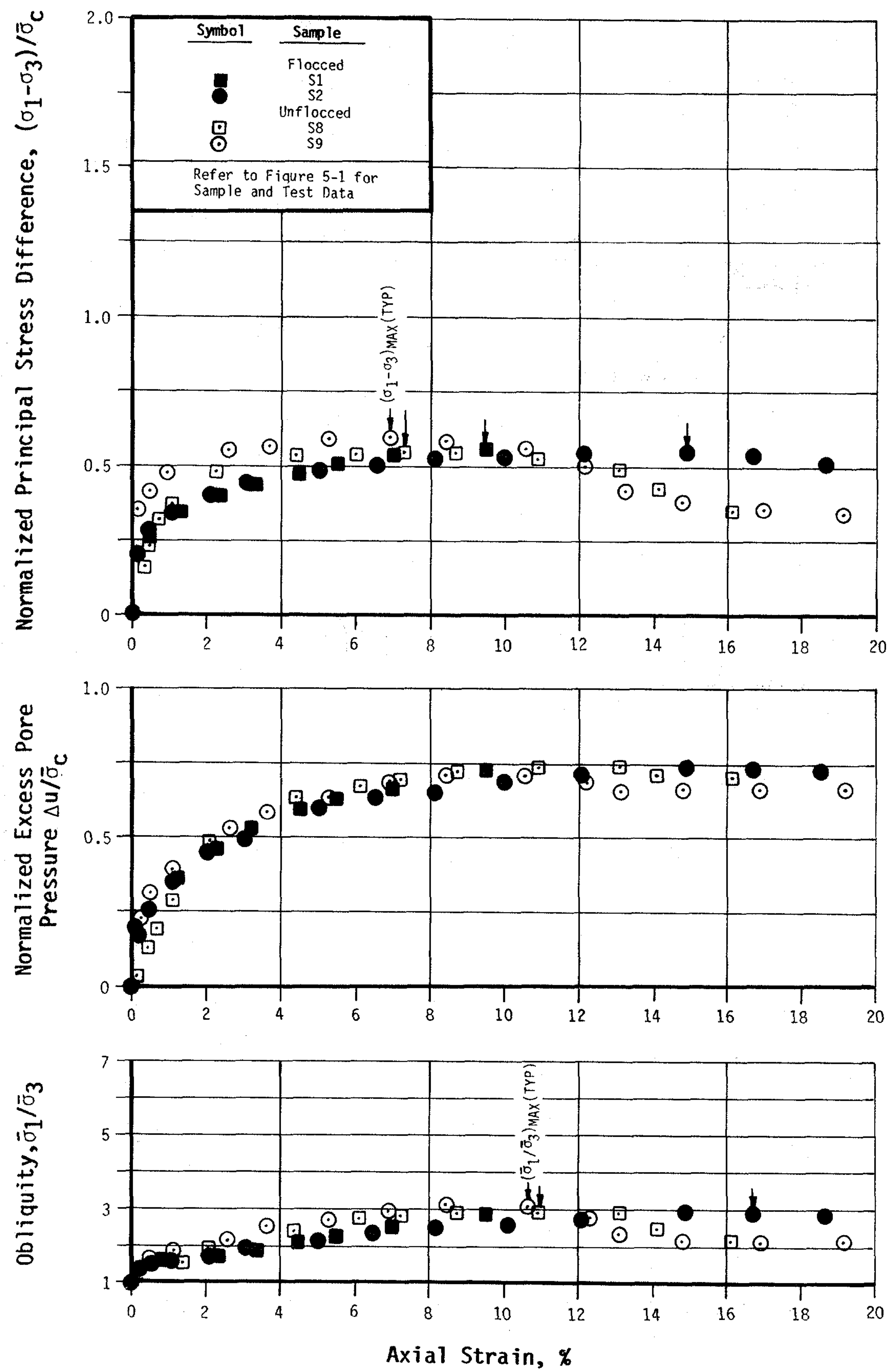


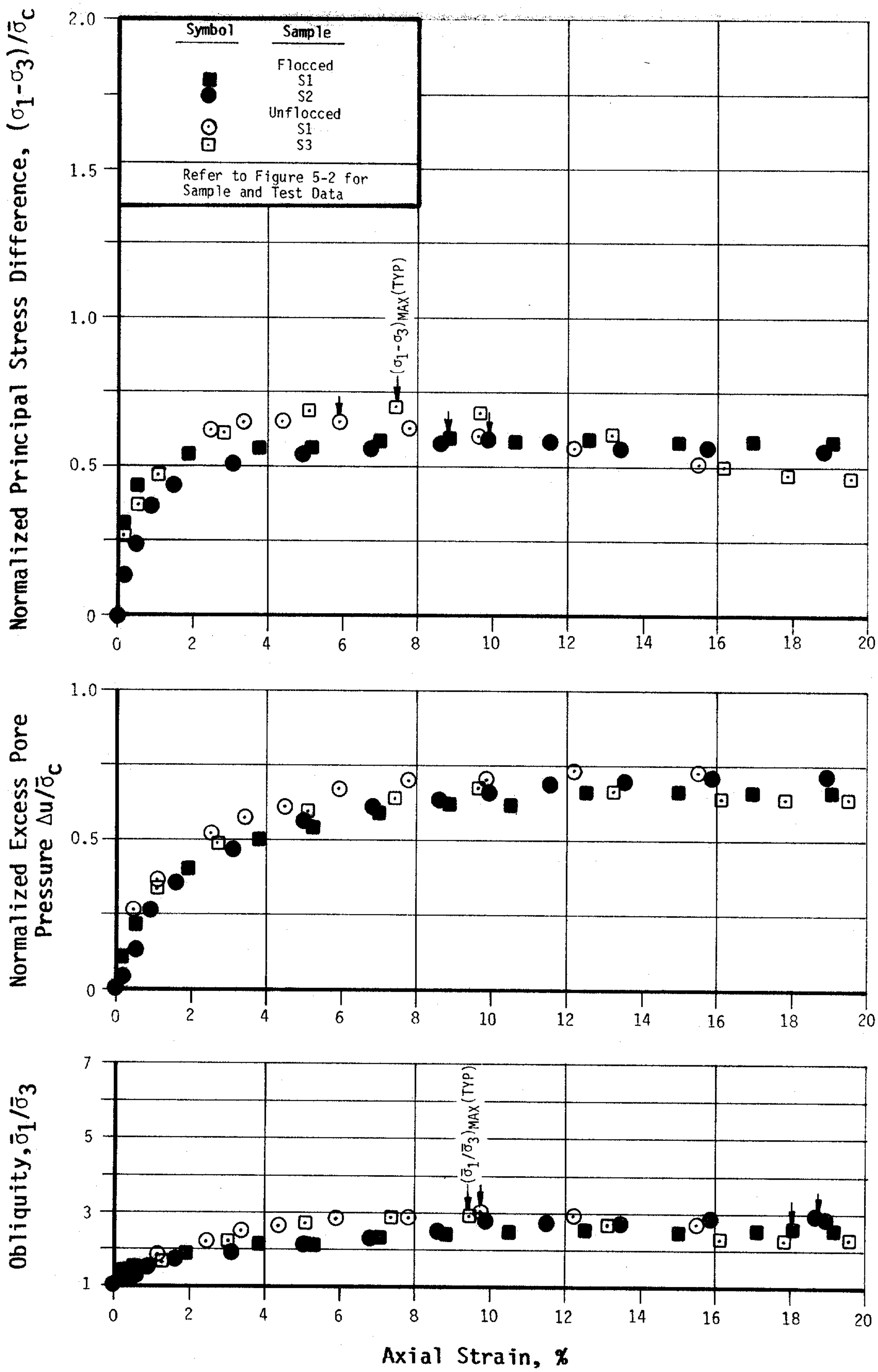
FIGURE 5-3

UNDRAINED EFFECTIVE STRESS PATHS FROM CIUC TESTS ON NORMALLY CONSOLIDATED USSAC-ROCKLAND UNFLOCCED CLAY AND CLAY AT OPTIMUM FLOCCULANT LOADING RATE



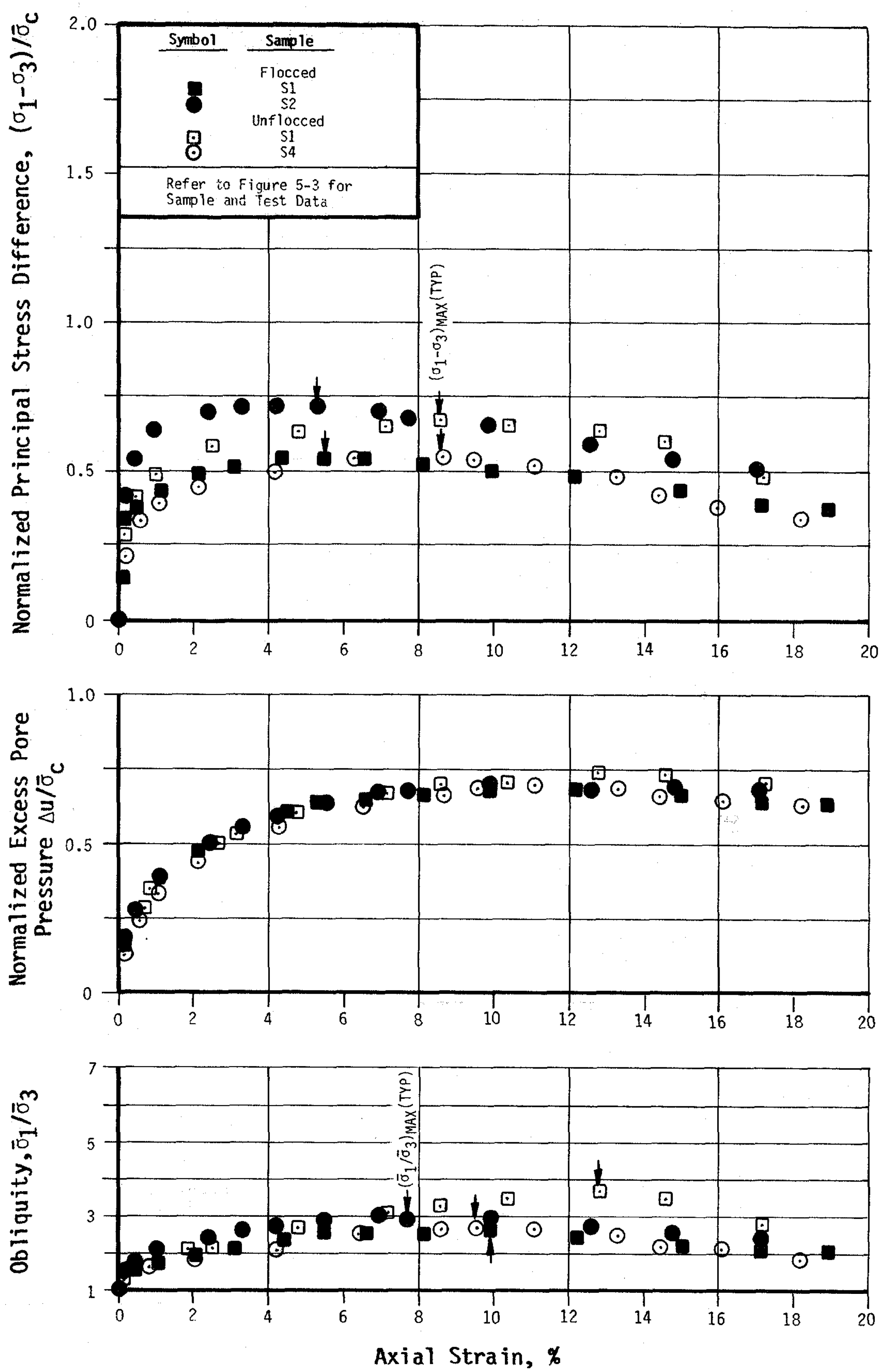
UNDRAINED STRESS-STRAIN BEHAVIOR FROM CIUC TESTS ON NORMALLY CONSOLIDATED AGRICO-SADDLE CREEK UNFLOCCED CLAY AND CLAY AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 5-4



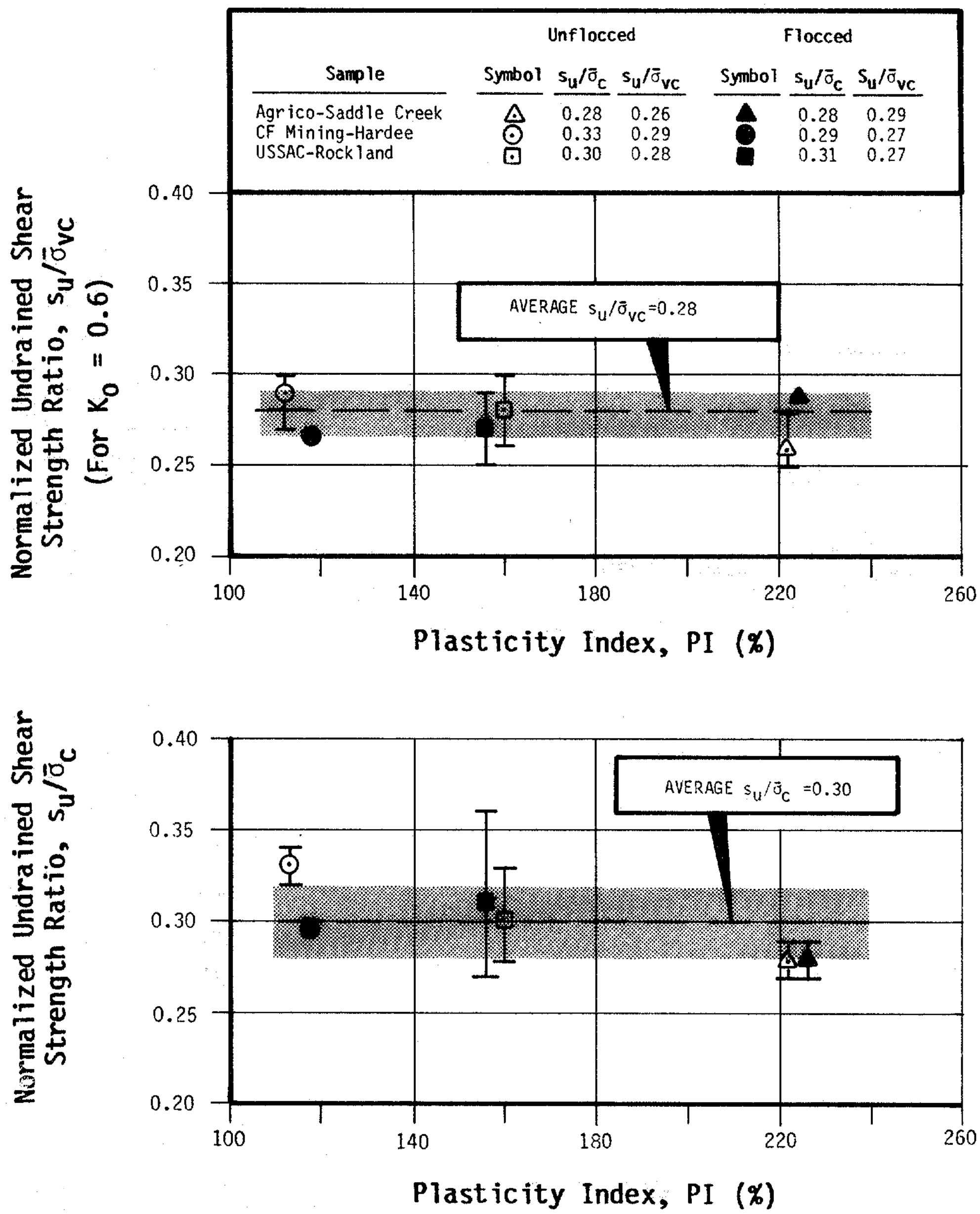
UNDRAINED STRESS-STRAIN BEHAVIOR FROM $\overline{\text{CIU}}$C TESTS ON NORMALLY CONSOLIDATED CF MINING-HARDEE UNFLOCCED CLAY AND CLAY AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 5-5



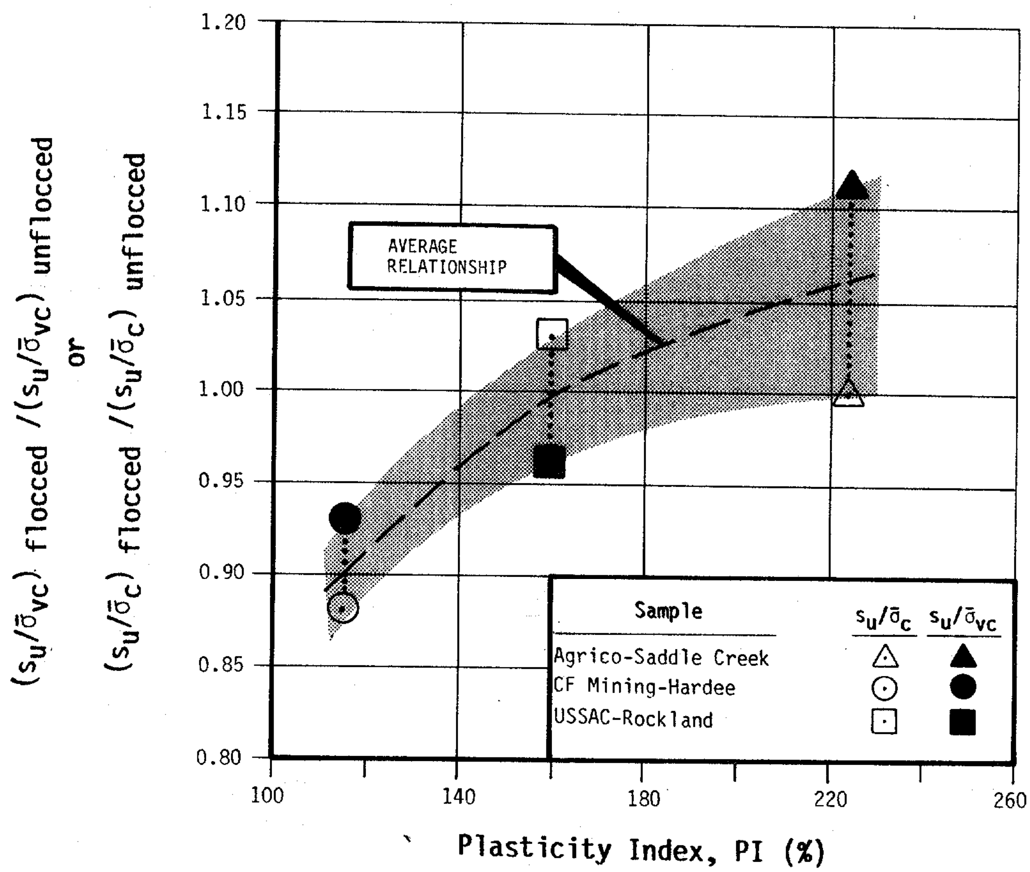
UNDRAINED STRESS-STRAIN BEHAVIOR FROM CIUC TESTS ON NORMALLY CONSOLIDATED USSAC-ROCKLAND UNFLOCCED CLAY AND CLAY AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 5-6



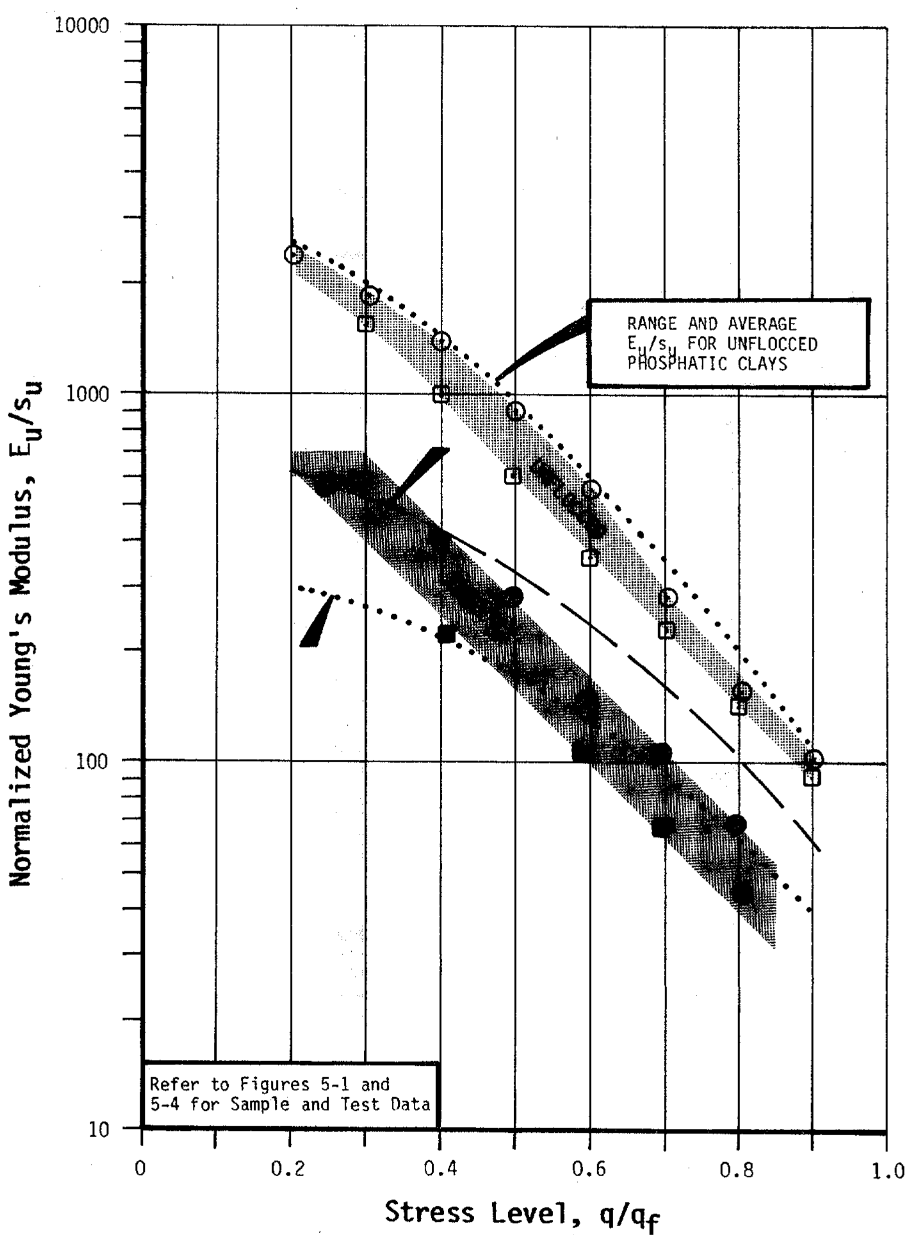
NORMALIZED UNDRAINED SHEAR STRENGTH RATIO VS. PLASTICITY INDEX FROM CIUC TESTS ON NORMALLY CONSOLIDATED UNFLOCCED CLAYS AND CLAYS AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 5-7



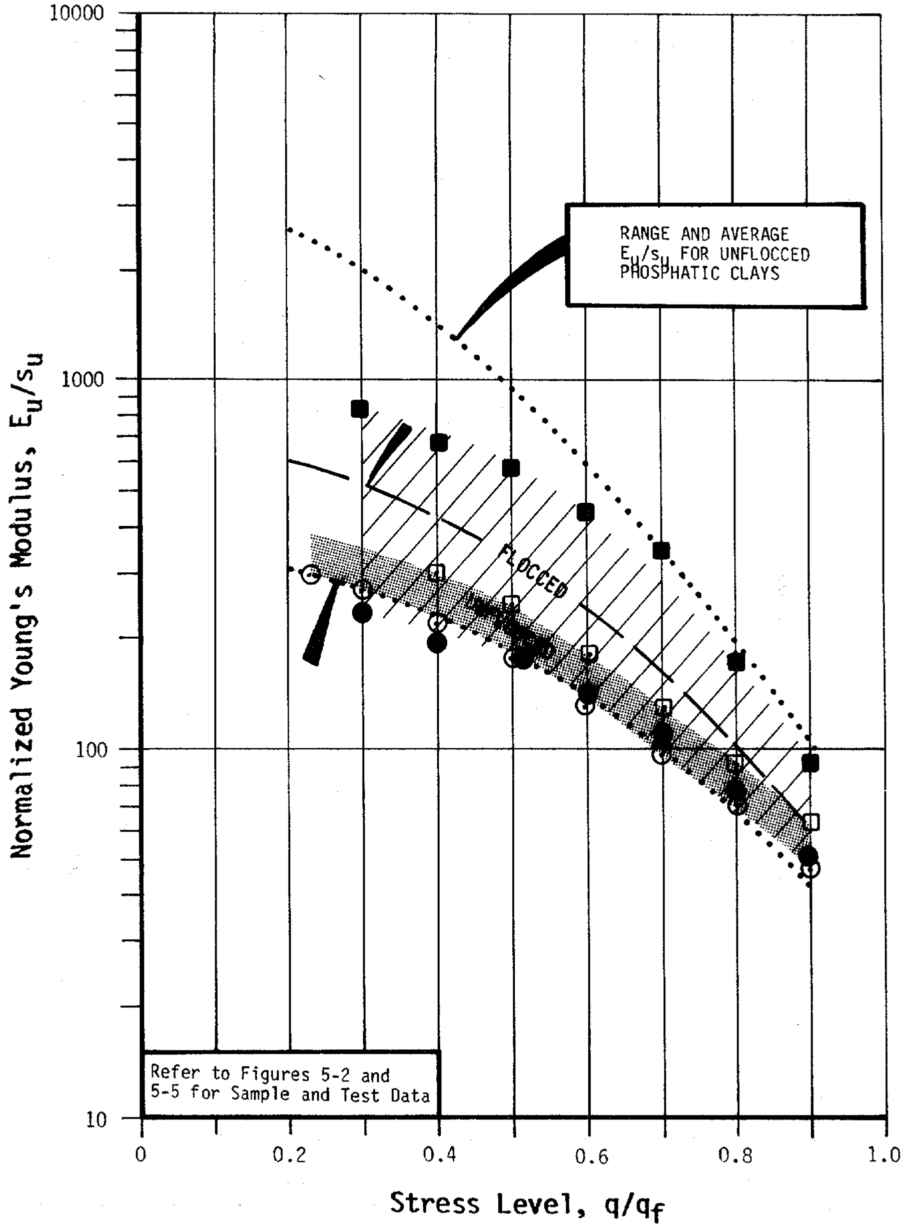
EFFECT OF FLOCCULATION ON NORMALIZED UNDRAINED SHEAR STRENGTH RATIO

FIGURE 5-8



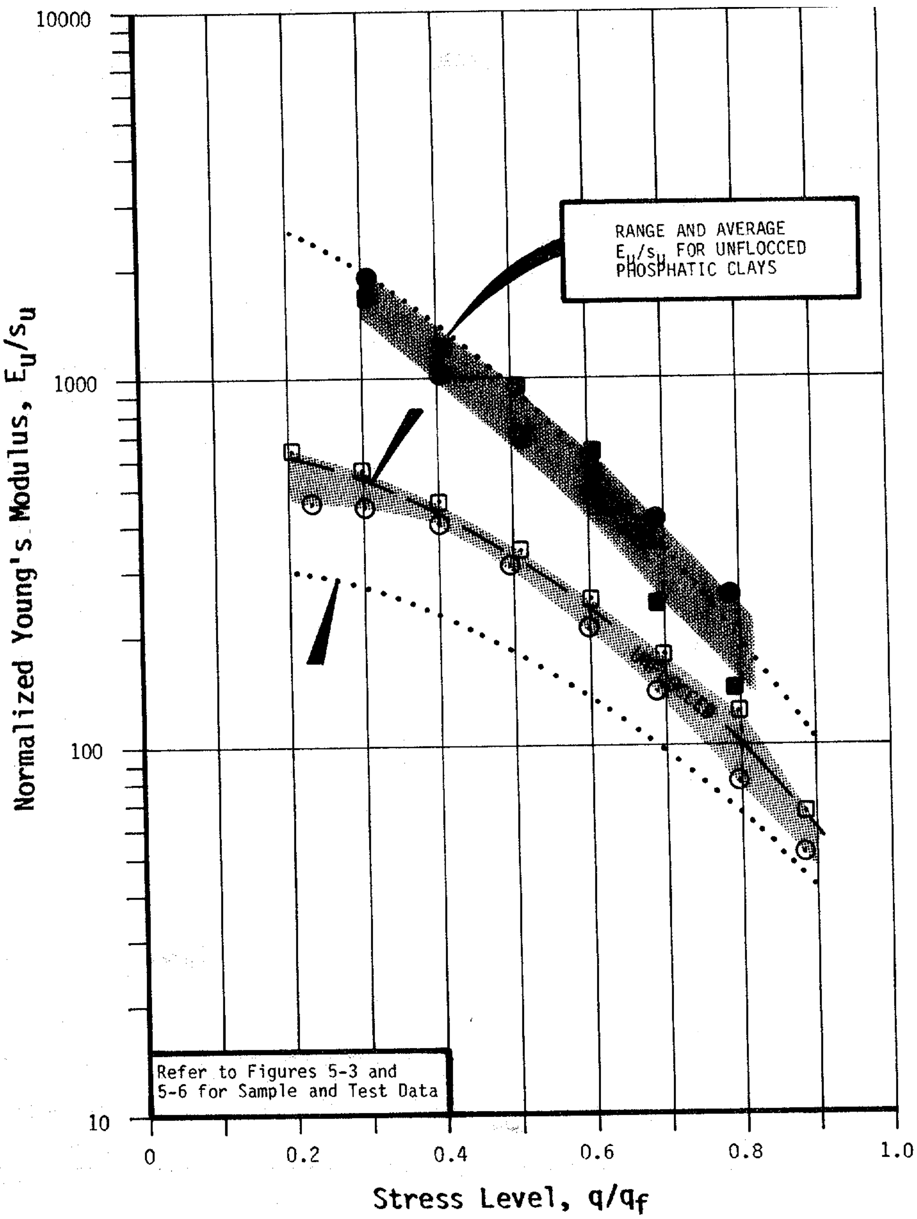
NORMALIZED UNDRAINED YOUNG'S SECANT MODULUS VS. STRESS LEVEL FROM CIUC TESTS ON NORMALLY CONSOLIDATED AGRICO-SADDLE CREEK UNFLOCCED CLAY AND CLAY AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 5-9



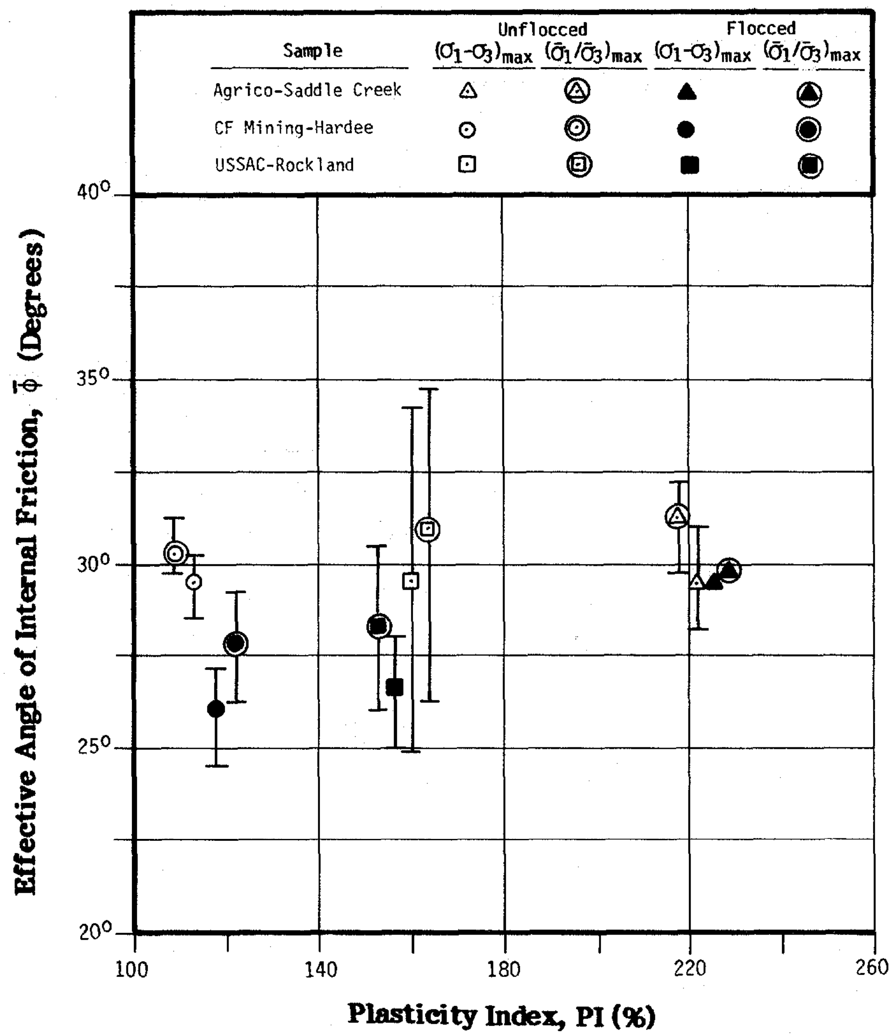
NORMALIZED UNDRAINED YOUNG'S SECANT MODULUS VS. STRESS LEVEL FROM CIUC TESTS ON NORMALLY CONSOLIDATED CF MINING-HARDEE UNFLOCCED CLAY AND CLAY AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 5-10



NORMALIZED UNDRAINED YOUNG'S SECANT MODULUS VS. STRESS LEVEL FROM CUIC TESTS ON NORMALLY CONSOLIDATED USSAC-ROCKLAND UNFLOCCED CLAY AND CLAY AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 5-11



EFFECTIVE ANGLE OF INTERNAL FRICTION VS. PLASTICITY INDEX FROM CIUC TESTS ON NORMALLY CONSOLIDATED UNFLOCCED CLAYS AND CLAYS AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE 5-12

Section 6

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Appendix A

SUMMARY OF TEST RESULTS FROM CONSTANT AND VARIABLE INITIAL HEIGHT SETTLING TESTS AT "OPTIMUM" FLOCCULANT LOADING RATE

Table A-1

SETTLING TEST RESULTS FOR AGRICO-SADDLE CREEK FLOCCULATED PHOSPHATIC CLAY AT "OPTIMUM" FLOCCULANT LOADING RATE

Initial Conditions						Initial Settling	t=100 minutes		Final Conditions	
S_i (%)	Z_o (cm)	S_{if} (%)	Z_{of} (cm)	ϕ_K	$Z_o\phi_K$ (cm)	Rate, Q_o (cm/min)	S (%)	Q_s (cm/min)	S_F (%)	Z_F (cm)
1.0	23.1	0.96	24.1	0.0036	0.08	32.4	4.36	0.19	5.60	4.0
3.0	5.4	2.75	6.0	0.0110	0.06	2.0	4.34	0.02	5.09	3.2
3.0	10.7	2.75	11.9	0.0110	0.12	3.6	5.16	0.06	5.64	5.7
3.0	16.1	2.77	17.8	0.0110	0.18	8.6	5.71	0.09	6.42	7.5
3.0	21.5	2.75	23.9	0.0110	0.24	16.4	6.00	0.13	6.75	9.5
3.0	35.7	2.73	40.0	0.0110	0.39	19.2	6.32	0.23	7.41	14.3
8.0	4.5	6.23	5.8	0.0304	0.14	0.04	7.32	0.01	7.94	4.5
8.0	9.0	6.23	11.6	0.0304	0.27	0.04	6.95	0.01	8.29	8.6
8.0	13.6	6.24	17.5	0.0304	0.41	0.02	6.73	0.01	8.35	12.9
8.0	18.0	6.15	23.5	0.0304	0.55	0.02	6.48	0.01	8.43	16.9

- Nomenclature: S_i = Initial unflocced clay solids content; Z_o = Initial height of unflocced clay suspension; S_{if} = Initial flocced clay solids content; Z_{of} = Initial height of flocced clay suspension; ϕ_K = Clay volume concentration; $Z_o\phi_K$ = Height of clay solids; Q_o = Initial settling rate; S = Settled solids content at 100 minutes; Q_s = Secant settling rate at 100 minutes; t = Time since beginning of test; S_F = "Final" settled solids content; Z_F = "Final" settled height.
- Flocculant: Flocculant = NALCO 7877 acrylamide polymer emulsion. Flocculant Loading Rate = 2.4 pounds of polymer per ton of clay.
- Clay Index Properties: Liquid Limit = 291%; Plasticity Index = 225%; Specific Gravity = 2.774

Table A-2

SETTLING TEST RESULTS FOR CF MINING-HARDEE FLOCCULATED PHOSPHATIC CLAY AT "OPTIMUM" FLOCCULANT LOADING RATE

Initial Conditions						Initial Settling	t=100 minutes		Final Conditions	
S_i (%)	Z_o (cm)	S_{if} (%)	Z_{of} (cm)	ϕ_K	$Z_o\phi_K$ (cm)	Rate, Q_o (cm/min)	S (%)	Q_s (cm/min)	S_F (%)	Z_F (cm)
1.0	23.8	0.99	24.0	0.0036	0.09	46.3	9.02	0.22	13.28	1.7
3.0	5.9	2.85	6.2	0.0109	0.06	20.0	8.85	0.04	12.70	1.3
3.0	11.6	2.89	12.0	0.0109	0.13	35.0	9.62	0.09	13.46	2.4
3.0	17.5	2.91	18.0	0.0109	0.19	40.0	10.41	0.13	13.88	3.5
3.0	23.3	2.90	24.0	0.0109	0.25	46.4	10.63	0.18	12.78	5.1
3.0	53.0	2.89	54.6	0.0109	0.58	61.5	11.07	0.41	14.33	10.2
5.0	22.8	4.78	24.0	0.0183	0.42	5.6	10.57	0.14	13.60	7.9
8.0	5.5	7.57	5.8	0.0300	0.17	0.010	8.08	0.004	14.90	2.8
8.0	11.0	7.39	11.9	0.0300	0.33	0.007	7.62	0.004	15.14	5.5
8.0	16.6	7.45	17.8	0.0300	0.50	0.005	7.60	0.004	15.65	8.0
8.0	21.4	7.43	23.0	0.0300	0.64	0.010	7.55	0.004	16.24	9.9

- Nomenclature: S_i = Initial unflocced clay solids content; Z_o = Initial height of unflocced clay suspension; S_{if} = Initial flocced clay solids content; Z_{of} = Initial height of flocced clay suspension; ϕ_K = Clay volume concentration; $Z_o\phi_K$ = Height of clay solids; Q_o = Initial settling rate; S = Settled solids content at 100 minutes; Q_s = Secant settling rate at 100 minutes; t = Time since beginning of test; S_F = "Final" settled solids content; Z_F = "Final" settled height.

- Flocculant: Flocculant = NALCO 7877 acrylamide polymer emulsion. Flocculant Loading Rate = 0.6 pounds of polymer per ton of clay.

- Clay Index Properties: Liquid Limit = 154%; Plasticity Index = 118%; Specific Gravity = 2.816

Table A-3

SETTLING TEST RESULTS FOR USSAC-ROCKLAND FLOCCULATED PHOSPHATIC CLAY AT "OPTIMUM" FLOCCULANT LOADING RATE

Initial Conditions						Initial Settling	t=100 minutes		Final Conditions	
S_i (%)	Z_o (cm)	S_{if} (%)	Z_{of} (cm)	ϕ_K	$Z_o\phi_K$ (cm)	Rate, Q_o (cm/min)	S (%)	Q_s (cm/min)	S_F (%)	Z_F (cm)
1.0	23.6	1.01	24.0	0.0036	0.08	38.6	5.62	0.20	7.08	3.3
3.0	5.7	2.82	6.0	0.0111	0.06	3.0	5.55	0.03	7.16	2.3
3.0	11.3	2.80	12.0	0.0111	0.13	7.0	6.31	0.07	7.57	4.3
3.0	17.0	2.81	18.0	0.0111	0.19	7.6	6.33	0.10	7.76	6.3
3.0	22.6	2.88	23.8	0.0111	0.25	4.1	6.01	0.13	8.37	7.9
3.0	47.1	2.86	49.9	0.0111	0.52	29.7	7.31	0.31	9.68	14.1
8.0	5.1	6.95	5.9	0.0305	0.16	0.005	7.22	0.002	8.98	4.5
8.0	10.3	7.07	11.7	0.0305	0.31	0.002	7.19	0.002	9.57	8.5
8.0	15.5	6.92	18.0	0.0305	0.47	0.002	6.96	0.001	9.85	12.4
8.0	20.6	6.98	23.7	0.0305	0.63	0.006	7.07	0.003	10.13	16.0

- Nomenclature: S_i = Initial unflocced clay solids content; Z_o = Initial height of unflocced clay suspension; S_{if} = Initial flocced clay solids content; Z_{of} = Initial height of flocced clay suspension; ϕ_K = Clay volume concentration; $Z_o\phi_K$ = Height of clay solids; Q_o = Initial settling rate; S = Settled solids content at 100 minutes; Q_s = Secant settling rate at 100 minutes; t = Time since beginning of test; S_F = "Final" settled solids content; Z_F = "Final" settled height.
- Flocculant: Flocculant = NALCO 7877 acrylamide polymer emulsion. Flocculant Loading Rate = 1.2 pounds of polymer per ton of clay.
- Clay Index Properties: Liquid Limit = 207%; Plasticity Index = 158%; Specific Gravity = 2.767

Appendix B

VOID RATIO VERSUS EFFECTIVE STRESS RELATIONSHIP DETERMINED FROM SETTLING TESTS AT "OPTIMUM" FLOCCULANT LOADING RATE

Table B-1

SETTLING TEST RESULTS FOR VOID RATIO VERSUS EFFECTIVE STRESS FOR AGRICO-SADDLE CREEK FLOCCULATED PHOSPHATIC CLAY AT "OPTIMUM" FLOCCULANT LOADING RATE

Total Sample				Lower 6 cm Increment of Sample				Void Ratio Versus Effective Stress Data		
Z_o (cm)	S_i (%)	Z_F (cm)	S_F (%)	Z_o (cm)	S_i (%)	Z_F (cm)	S_F (%)	e_f	γ_t (lb/ft^3)	$\bar{\sigma}_{vc}$ (lb/ft^2)
• Variable Initial Height Settling Tests										
6.0	3.0	3.2	5.09	6.0	3.0	3.2	5.09	51.72	64.51	0.111
12.0	3.0	5.7	5.64	6.0	3.0	2.5	6.40	40.57	65.02	0.329
18.0	3.0	7.5	6.42	6.0	3.0	1.8	8.77	28.86	66.12	0.547
24.0	3.0	9.5	6.75	6.0	3.0	2.0	7.95	32.12	65.76	0.767
40.0	3.0	14.3	7.41	16.0*	3.0	4.8	8.75	28.93	66.11	1.169
6.0	8.0	4.5	7.94	6.0	8.0	4.5	7.94	32.16	65.74	0.247
12.0	8.0	8.6	8.29	6.0	8.0	4.1	8.67	29.22	66.08	0.741
18.0	8.0	12.9	8.35	6.0	8.0	4.3	8.35	30.45	65.95	1.239
24.0	8.0	16.9	8.43	6.0	8.0	4.0	8.88	28.46	66.13	1.734
• Constant Initial Height Settling Tests										
23.7	3.0	9.2	6.19	-	-	-	-	42.04	64.96	0.386**

- Nomenclature: Z_o = Initial height of flocced clay suspension; S_i = Initial unflocced clay solids content; Z_F = "Final" settled height; S_F = "Final" settled solids content; e_f = "Final" void ratio; γ_t = Total unit weight; $\bar{\sigma}_{vc}$ = Effective vertical consolidation stress.
- Flocculant: Flocculant = NALCO 7877 acrylamide polymer emulsion. Flocculant Loading Rate = 2.4 pounds of polymer per ton of clay.
- Clay Index Properties: Liquid Limit = 291%; Plasticity Index = 225%; Specific Gravity = 2.774

* Void ratio vs. effective stress relationship for lower 16 cm of sample.
** Void ratio vs. effective stress relationship based on average conditions at midpoint of entire sample.

Table B-2

SETTLING TEST RESULTS FOR VOID RATIO VERSUS EFFECTIVE STRESS FOR CF MINING-HARDEE FLOCCULATED PHOSPHATIC CLAY AT "OPTIMUM" FLOCCULANT LOADING RATE

Total Sample				Lower 6 cm Increment of Sample				Void Ratio Versus Effective Stress Data		
Z_o (cm)	S_i (%)	Z_F (cm)	S_F (%)	Z_o (cm)	S_i (%)	Z_F (cm)	S_F (%)	e_f	γ_t (lb/ft^3)	$\bar{\sigma}_{vc}$ (lb/ft^2)
• Variable Initial Height Settling Tests										
6.0	3.0	1.3	12.70	6.0	3.0	1.3	12.71	19.34	67.96	0.119
12.0	3.0	2.4	13.46	6.0	3.0	1.1	15.36	15.52	65.31	0.290
18.0	3.0	3.5	13.88	6.0	3.0	1.1	14.65	16.41	68.91	0.460
24.0	3.0	5.1	12.78	6.0	3.0	1.6	10.36	24.37	66.89	0.695
54.6	3.0	10.2	14.33	30.6*	3.0	5.1	15.88	14.92	69.54	1.410
6.0	8.0	2.8	14.90	6.0	8.0	2.8	14.90	16.08	69.03	0.305
12.0	8.0	5.5	15.14	6.0	8.0	2.7	15.40	15.47	69.26	0.914
18.0	8.0	8.0	15.65	6.0	8.0	2.5	16.59	14.16	69.86	1.525
24.0	8.0	9.9	16.24	6.0	8.0	1.9	20.50	10.92	71.91	2.128
• Constant Initial Height Settling Tests										
24.1	3.0	4.9	13.45	-	-	-	-	18.12	67.64	0.421**

- Nomenclature: Z_o = Initial height of flocced clay suspension; S_i = Initial unflocced clay solids content; Z_F = "Final" settled height; S_F = "Final" settled solids content; e_f = "Final" void ratio; γ_t = Total unit weight; $\bar{\sigma}_{vc}$ = Effective vertical consolidation stress.
- Flocculant: Flocculant = NALCO 7877 acrylamide polymer emulsion. Flocculant Loading Rate = 0.6 pounds of polymer per ton of clay.
- Clay Index Properties: Liquid Limit = 154%; Plasticity Index = 118%; Specific Gravity = 2.816

* Void ratio vs. effective stress relationship for lower 30.6 cm of sample.
** Void ratio vs. effective stress relationship based on average conditions at midpoint of entire sample.

Table B-3

SETTLING TEST RESULTS FOR VOID RATIO VERSUS EFFECTIVE STRESS FOR USSAC-ROCKLAND FLOCCULATED PHOSPHATIC CLAY AT "OPTIMUM" FLOCCULANT LOADING RATE

Total Sample				Lower 6 cm Increment of Sample				Void Ratio Versus Effective Stress Data		
Z_o (cm)	S_i (%)	Z_F (cm)	S_F (%)	Z_o (cm)	S_i (%)	Z_F (cm)	S_F (%)	e_f	γ_t (lb/ft^3)	$\bar{\sigma}_{vc}$ (lb/ft^2)
• Variable Initial Height Settling Tests										
6.0	3.0	2.3	7.16	6.0	3.0	2.3	7.15	35.93	65.41	0.114
12.0	3.0	4.3	7.57	6.0	3.0	2.0	8.09	31.44	65.84	0.340
18.0	3.0	6.3	7.76	6.0	3.0	2.0	8.12	31.31	65.81	0.565
24.0	3.0	7.9	8.37	6.0	3.0	1.6	10.19	24.39	66.72	0.791
49.9	3.0	14.1	9.68	25.9*	3.0	6.2	11.28	21.76	67.28	1.401
6.0	8.0	4.5	8.98	6.0	8.0	4.5	8.98	28.05	66.23	0.283
12.0	8.0	8.5	9.57	6.0	8.0	4.0	10.13	24.55	66.69	0.847
18.0	8.0	12.4	9.85	6.0	8.0	3.9	10.40	23.84	66.83	1.412
24.0	8.0	16.0	10.13	6.0	8.0	3.6	11.17	22.00	67.20	1.979
• Constant Initial Height Settling Tests										
24.0	3.0	8.2	7.99	-	-	-	-	31.86	65.78	0.455**

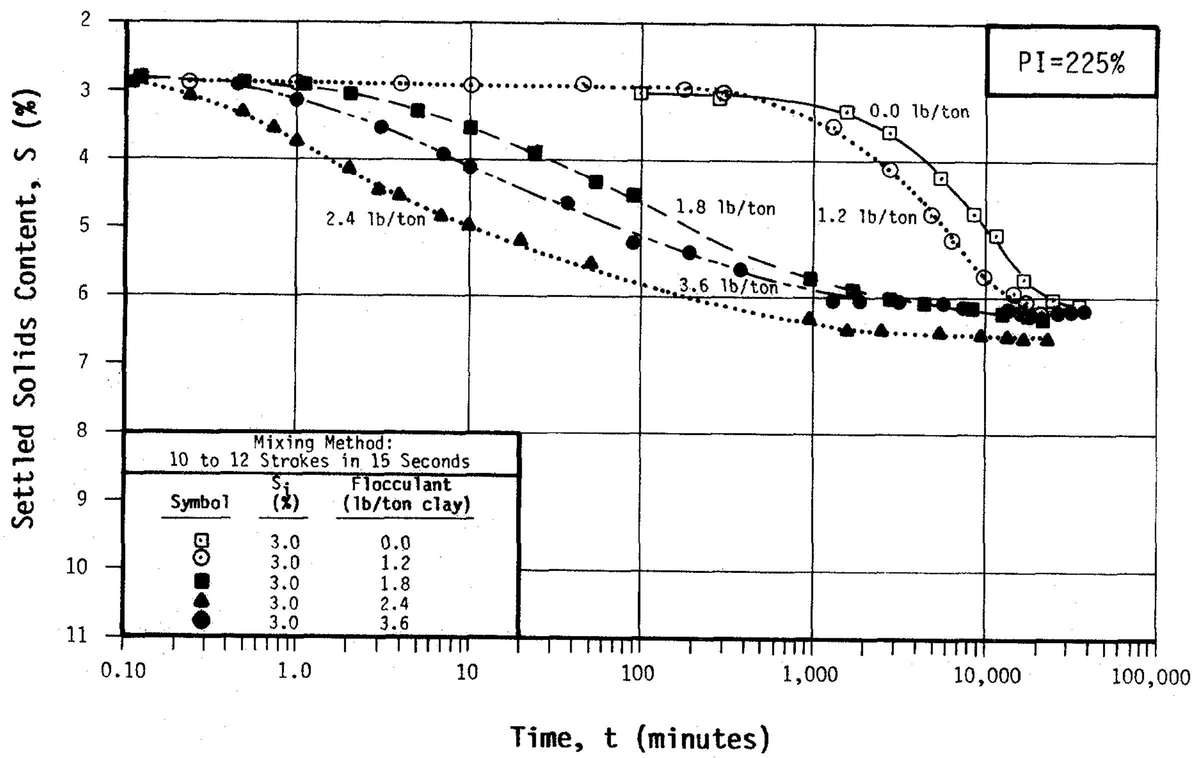
- Nomenclature: Z_o = Initial height of flocced clay suspension; S_i = Initial unflocced clay solids content; Z_F = "Final" settled height; S_F = "Final" settled solids content; e_f = "Final" void ratio; γ_t = Total unit weight; $\bar{\sigma}_{vc}$ = Effective vertical consolidation stress.
- Flocculant: Flocculant = NALCO 7877 acrylamide polymer emulsion. Flocculant Loading Rate = 1.2 pounds of polymer per ton of clay.
- Clay Index Properties: Liquid Limit = 207%; Plasticity Index = 158%; Specific Gravity = 2.767

* Void ratio vs. effective stress relationship for lower 25.9 cm of sample.

** Void ratio vs. effective stress relationship based on average conditions at midpoint of entire sample.

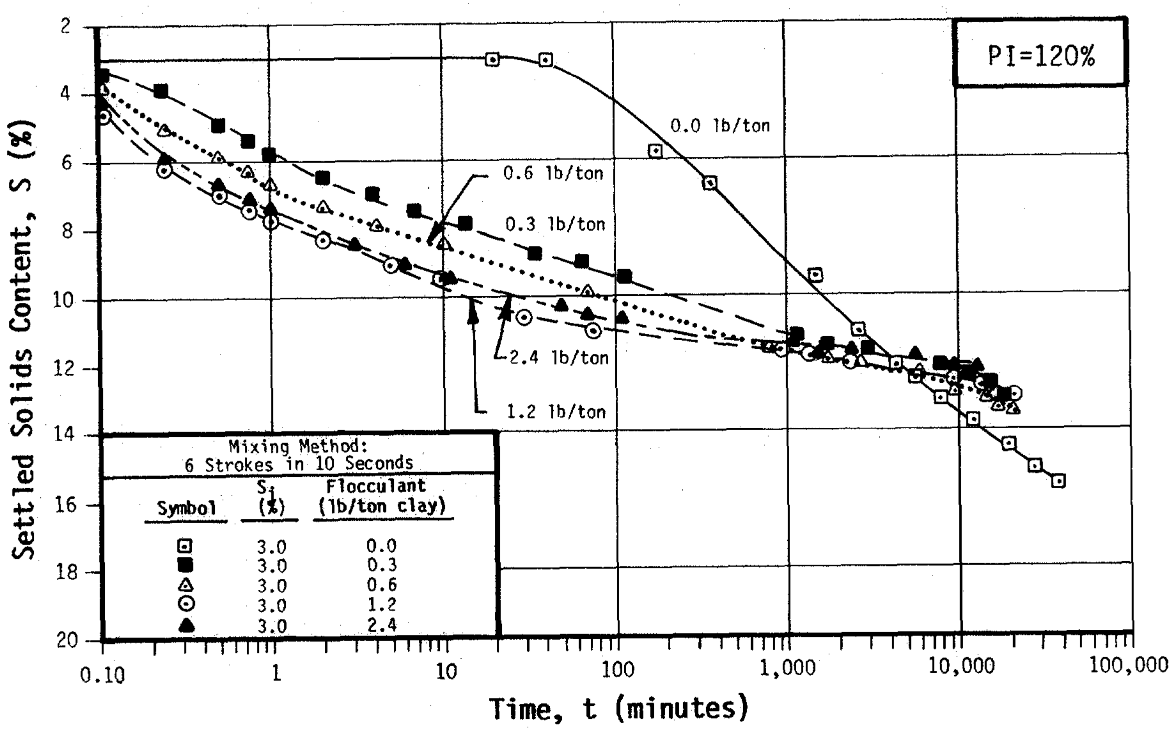
Appendix C

SOLIDS CONTENTS AND HEIGHT OF INTERFACE VERSUS TIME FOR SETTLING TESTS AT 3% INITIAL SOLIDS CONTENT WITH VARIOUS FLOCCULANT LOADING RATES



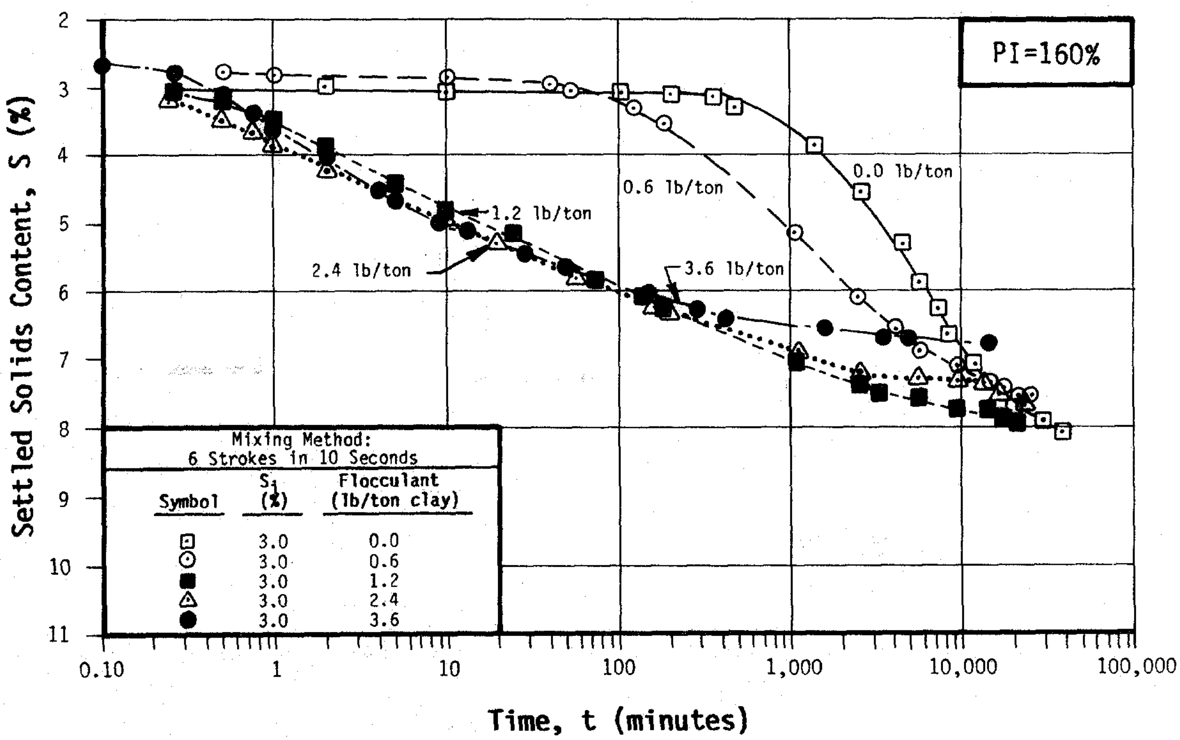
SOLIDS CONTENT VS. LOG TIME FOR AGRICO-SADDLE CREEK FLOCCULATED PHOSPHATIC CLAY

FIGURE C-1



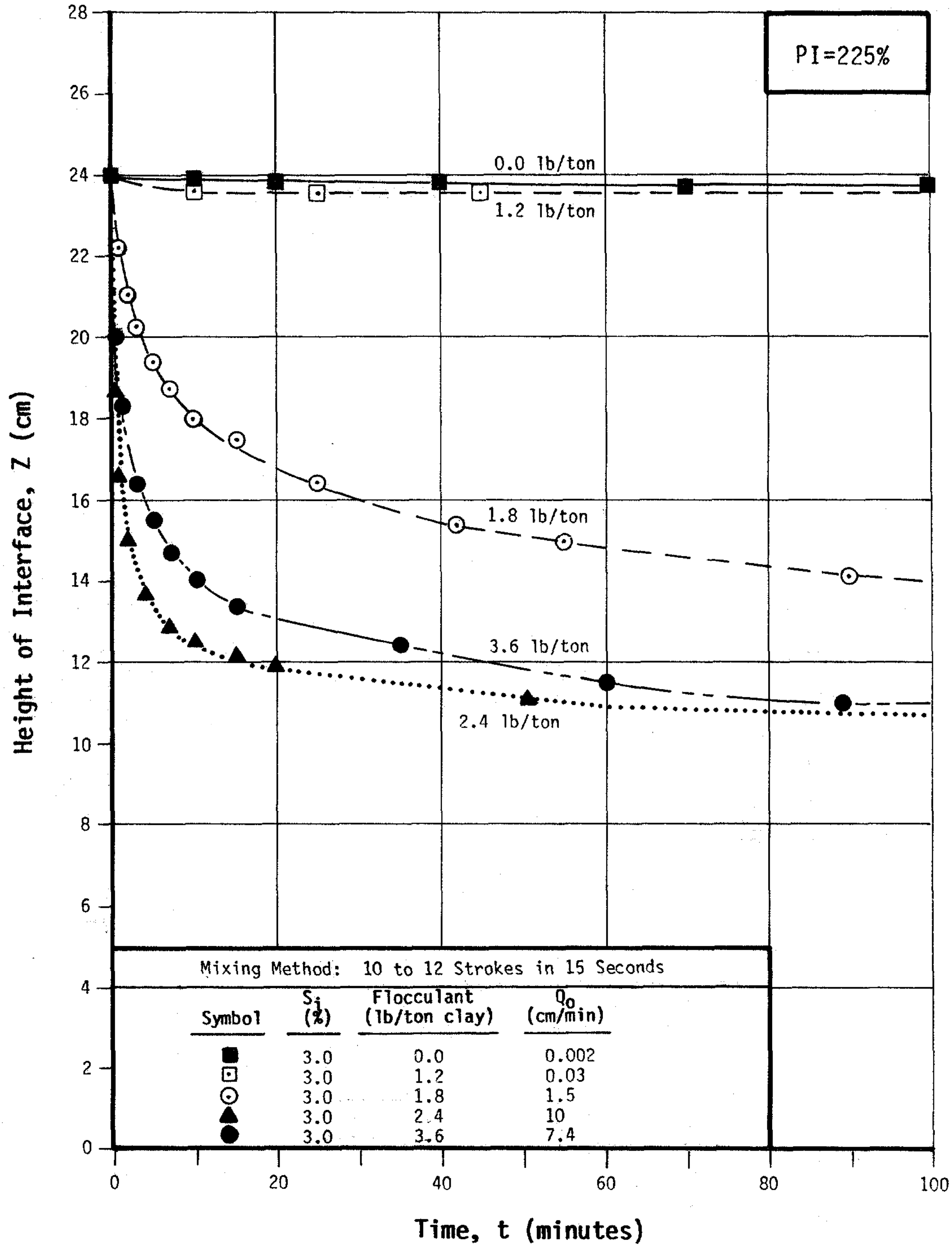
SOLIDS CONTENT VS. LOG TIME FOR CF MINING-HARDEE FLOCCULATED PHOSPHATIC CLAY

FIGURE C-2



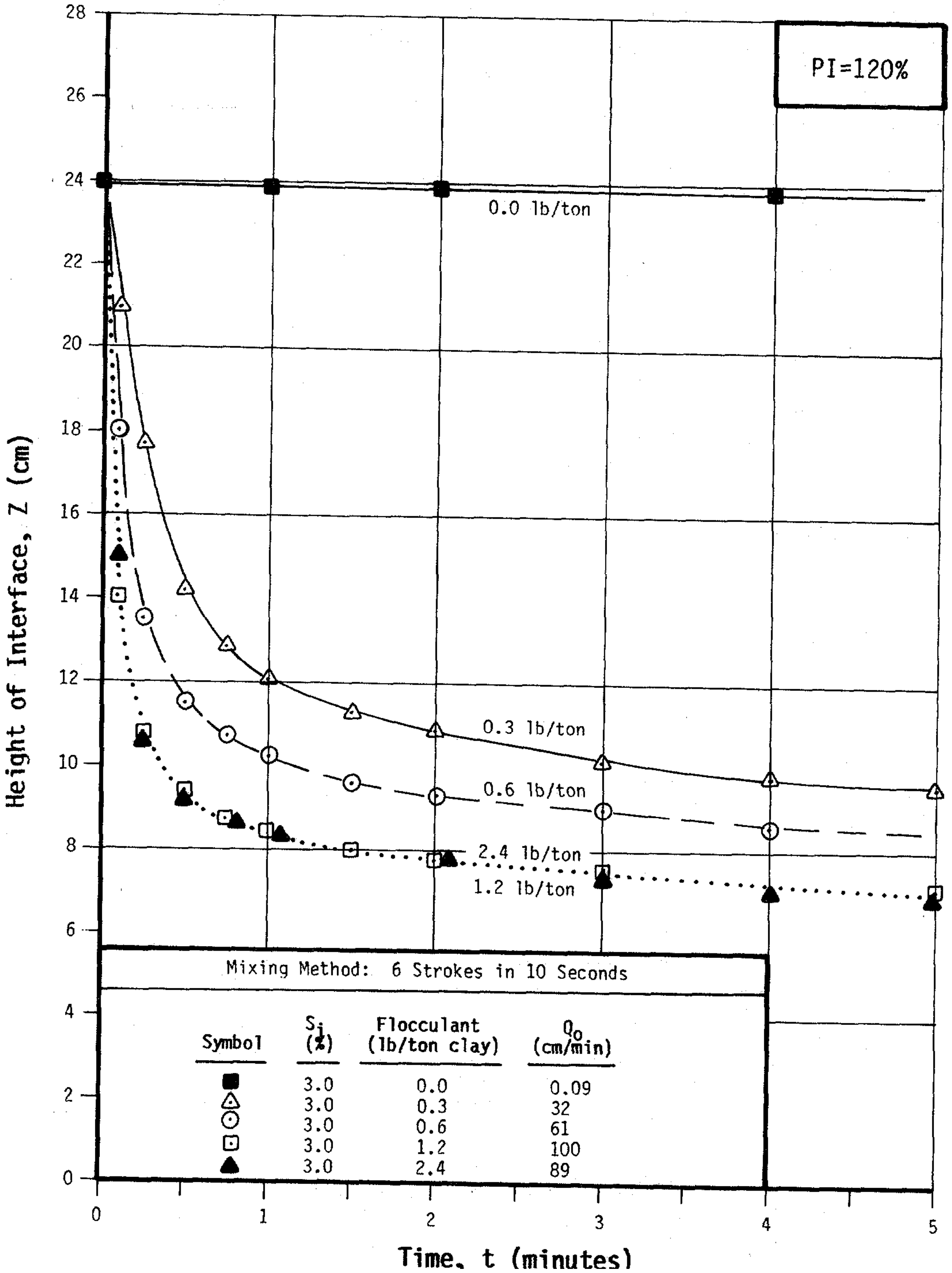
SOLIDS CONTENT VS. LOG TIME FOR USSAC-ROCKLAND FLOCCULATED PHOSPHATIC CLAY

FIGURE C-3



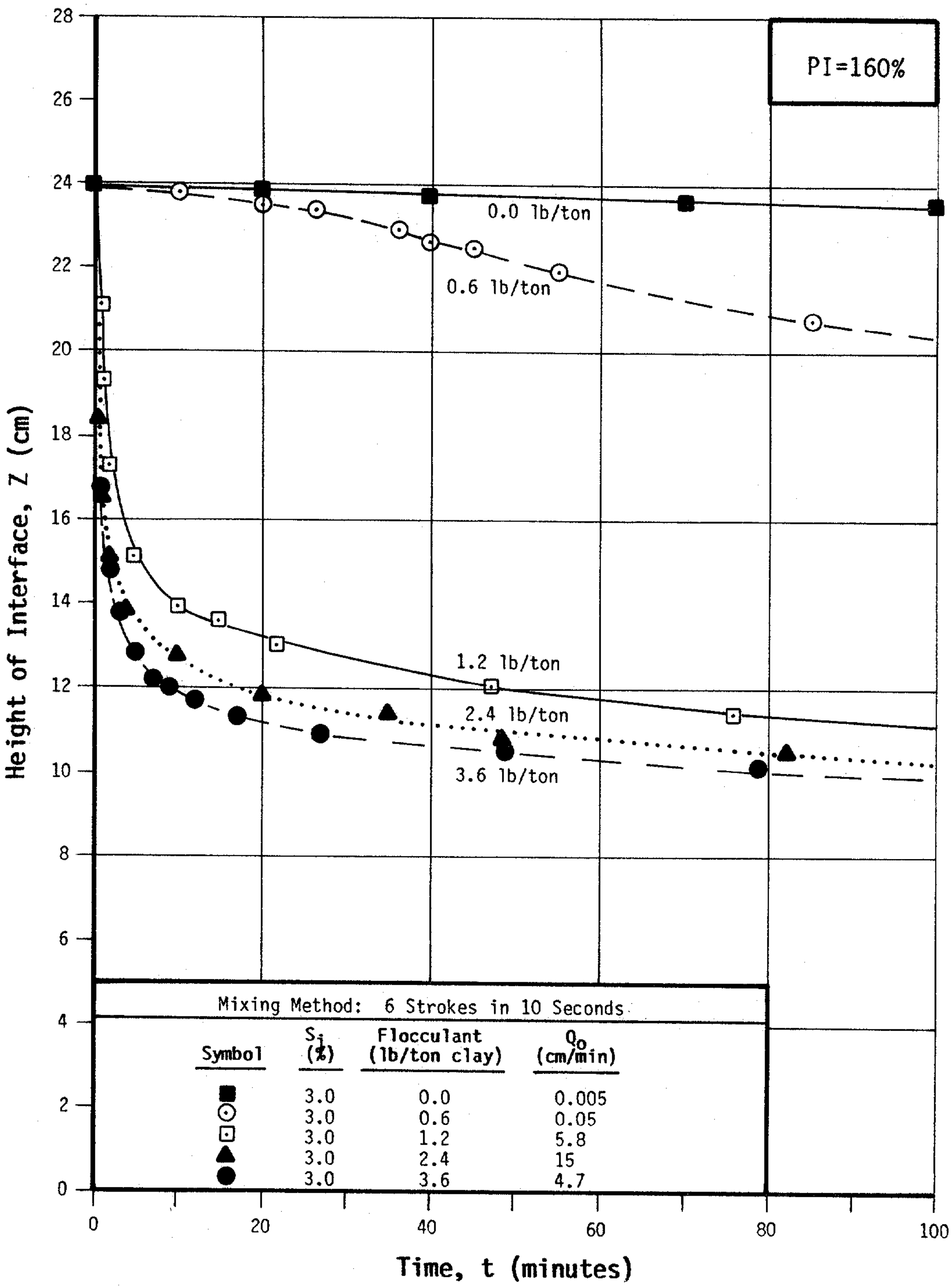
HEIGHT VS. TIME SETTLING TEST RESULTS FOR AGRICO-SADDLE CREEK FLOCCULATED PHOSPHATIC CLAY

FIGURE C-4



HEIGHT VS. TIME SETTLING TEST RESULTS FOR CF MINING-HARDEE FLOCCULATED PHOSPHATIC CLAY

FIGURE C-5

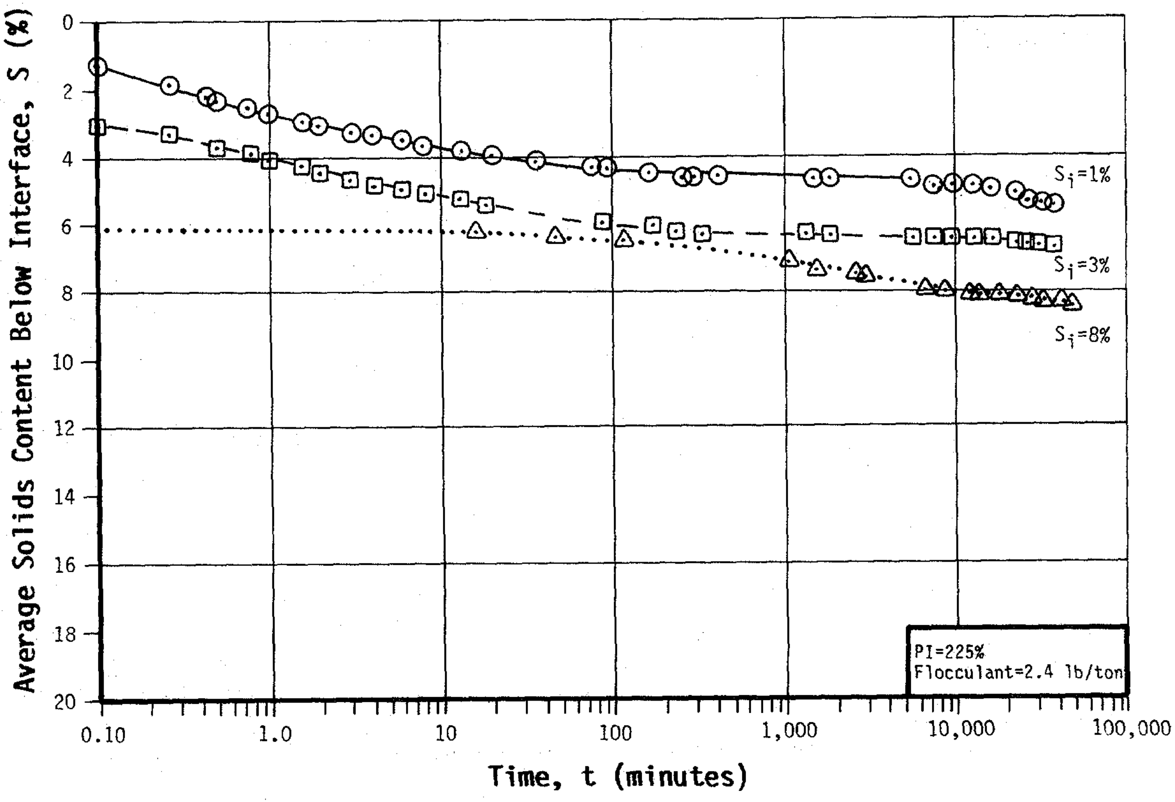


HEIGHT VS. TIME SETTLING TEST RESULTS FOR USSAC-ROCKLAND FLOCCULATED PHOSPHATIC CLAY

FIGURE C-6

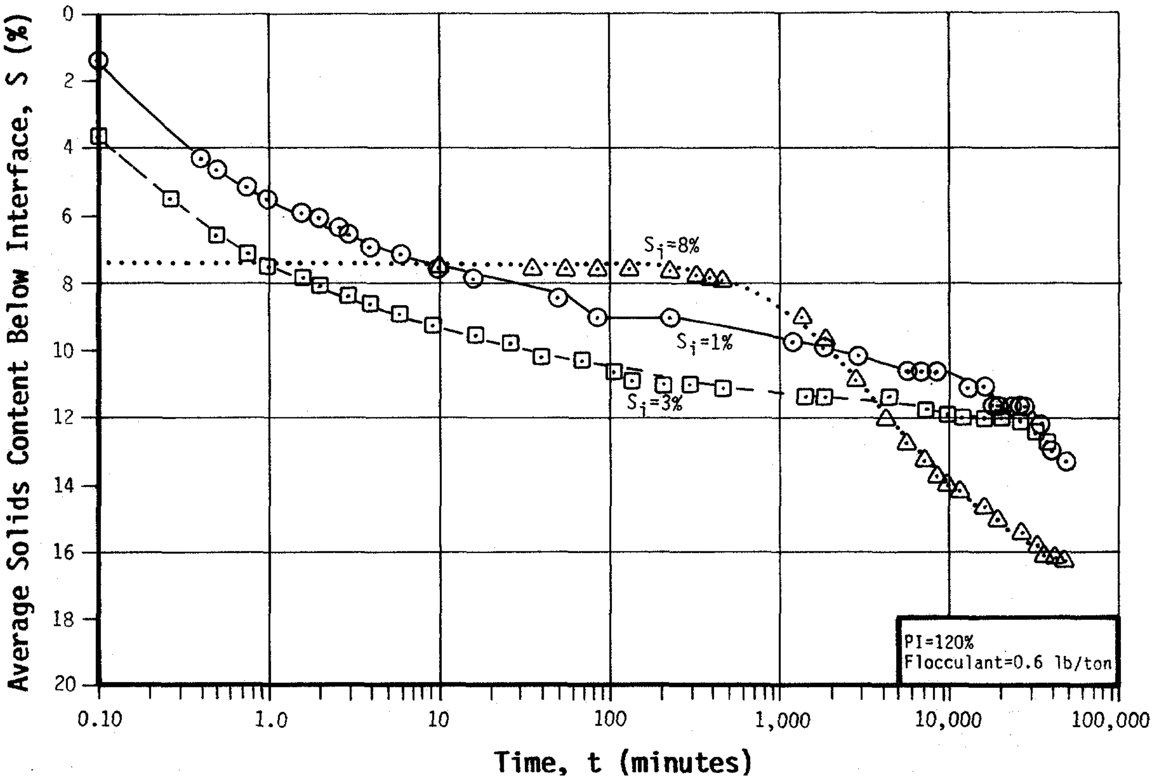
Appendix D

SOLIDS CONTENT AND HEIGHT OF INTERFACE VERSUS TIME FOR SETTLING TESTS WITH VARIOUS INITIAL SOLIDS CONTENTS AT “OPTIMUM” FLOCCULANT LOADING RATE



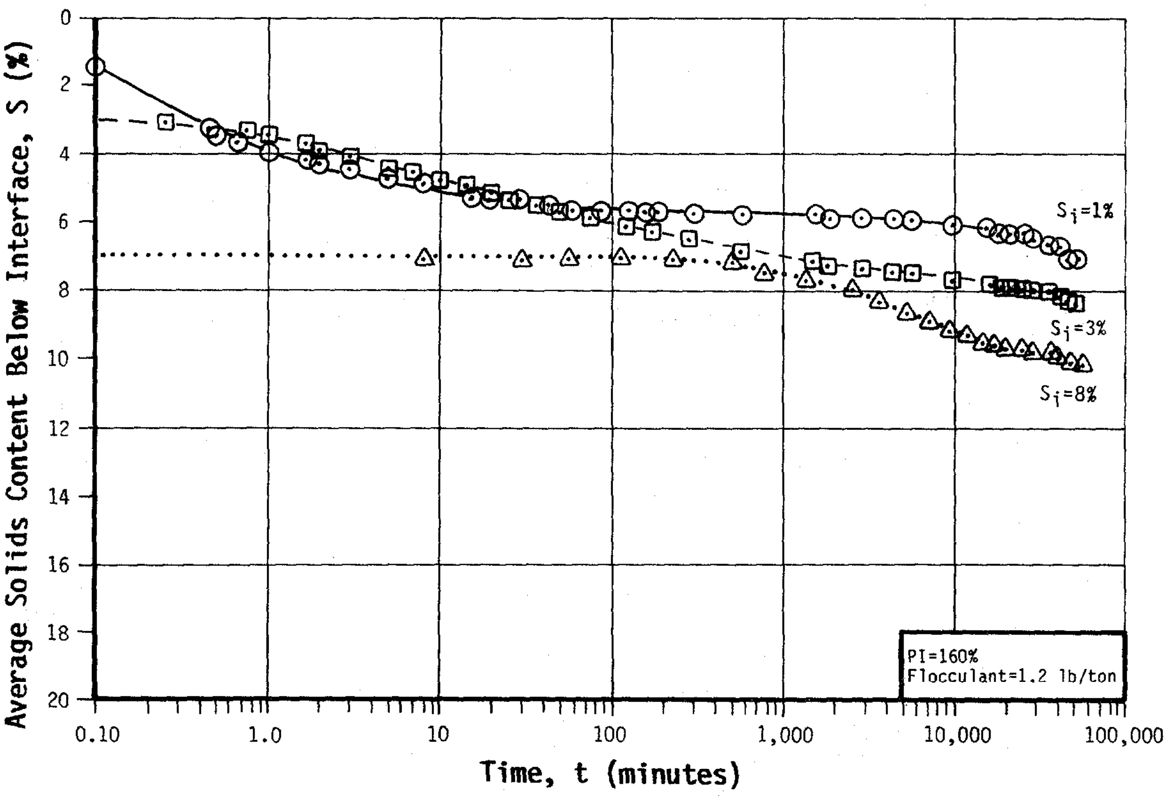
SOLIDS CONTENT VS. LOG TIME
FOR VARIOUS INITIAL SOLIDS CONTENTS
FOR AGRICO-SADDLE CREEK PHOSPHATIC CLAY
AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE D-1



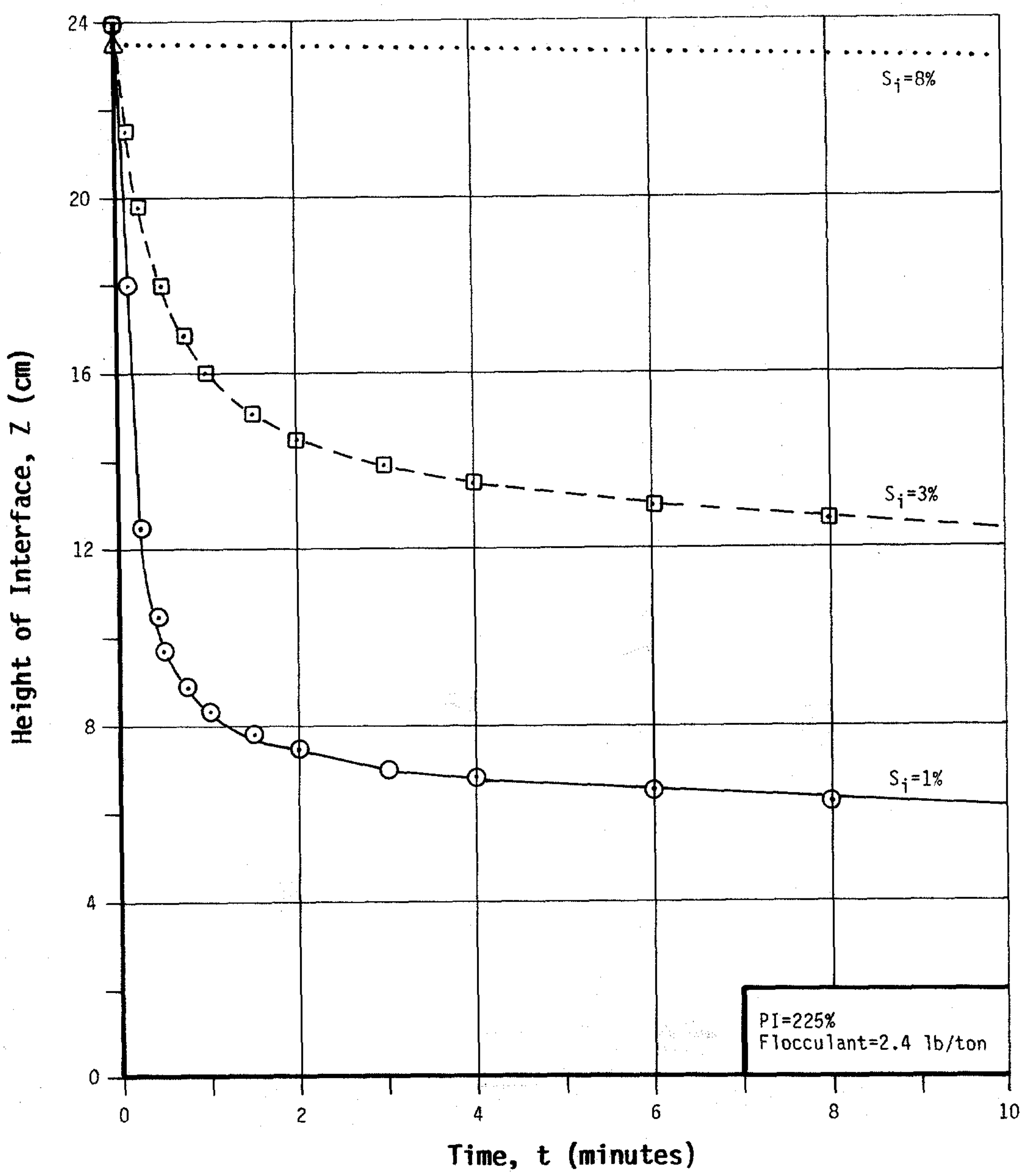
**SOLIDS CONTENT VS. LOG TIME
FOR VARIOUS INITIAL SOLIDS CONTENTS
FOR CF-MINING HARDEE PHOSPHATIC CLAY
AT OPTIMUM FLOCCULANT LOADING RATE**

FIGURE D-2



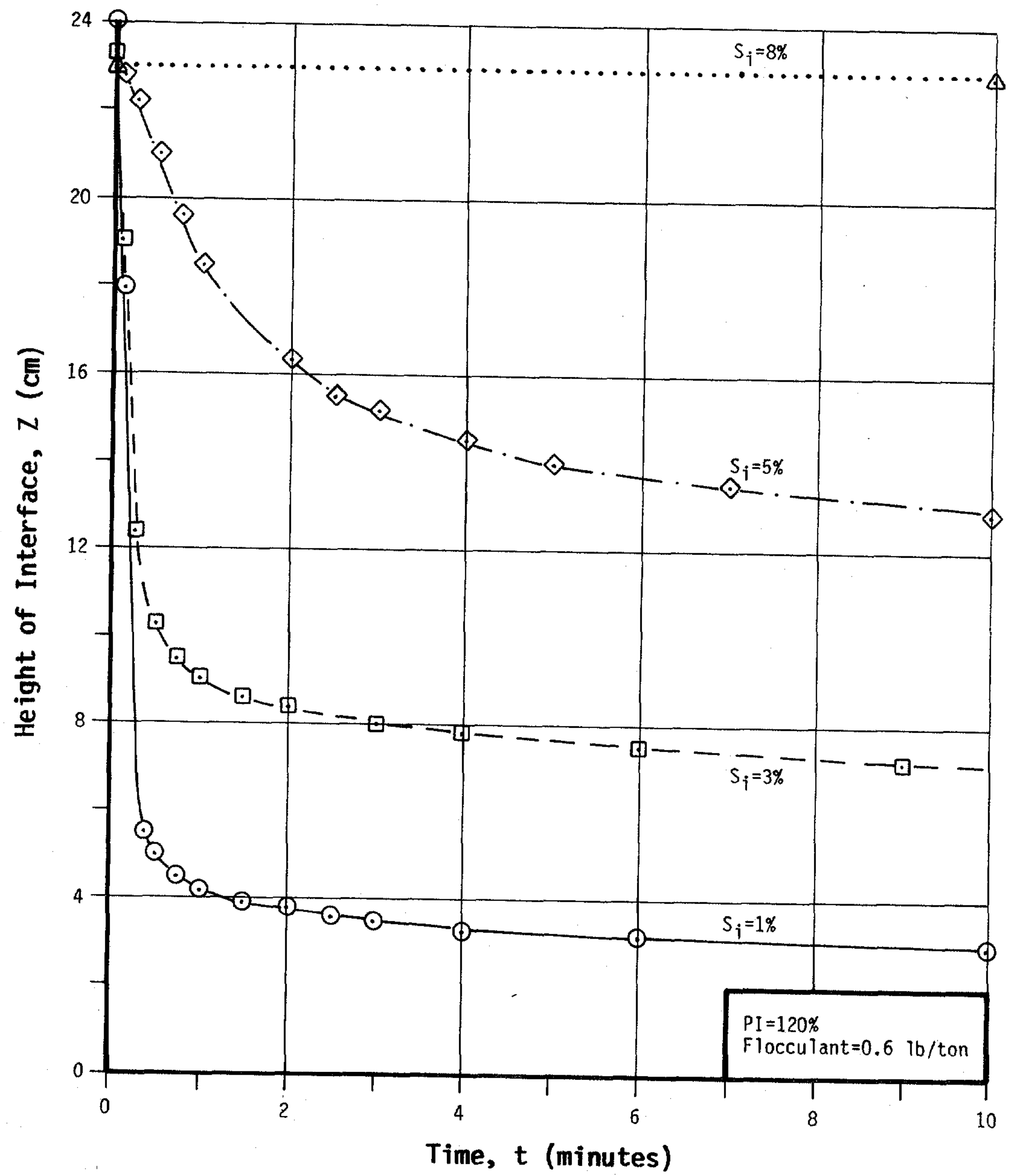
**SOLIDS CONTENT VS. LOG TIME
FOR VARIOUS INITIAL SOLIDS CONTENTS
FOR USSAC-ROCKLAND PHOSPHATIC CLAY
AT OPTIMUM FLOCCULANT LOADING RATE**

FIGURE D-3



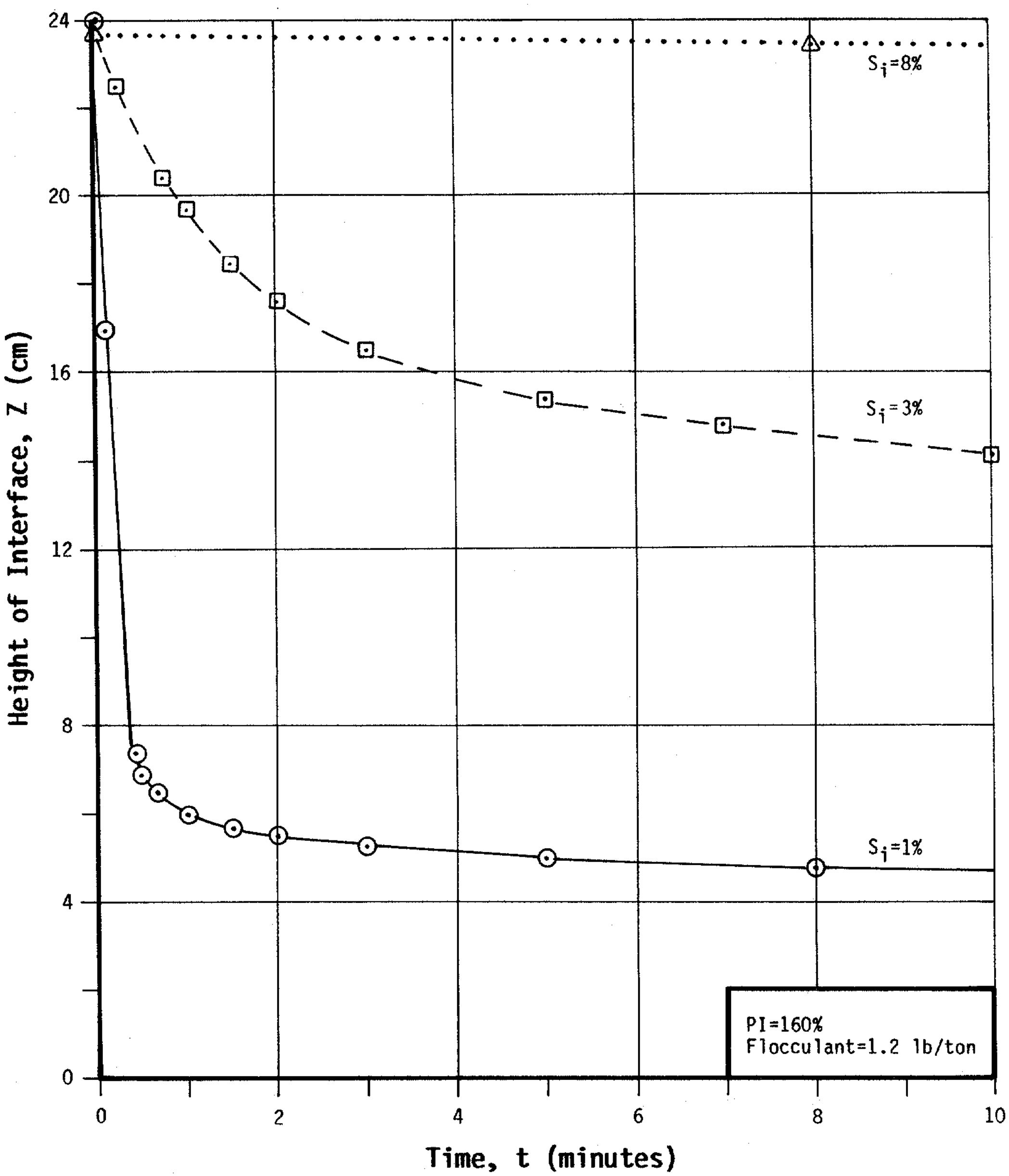
HEIGHT VS. TIME SETTLING TEST RESULTS FOR VARIOUS INITIAL SOLIDS CONTENTS FOR AGRICO-SADDLE CREEK PHOSPHATIC CLAY AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE D-4



HEIGHT VS. TIME SETTLING TEST RESULTS FOR VARIOUS INITIAL SOLIDS CONTENTS FOR CF-MINING HARDEE PHOSPHATIC CLAY AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE D-5

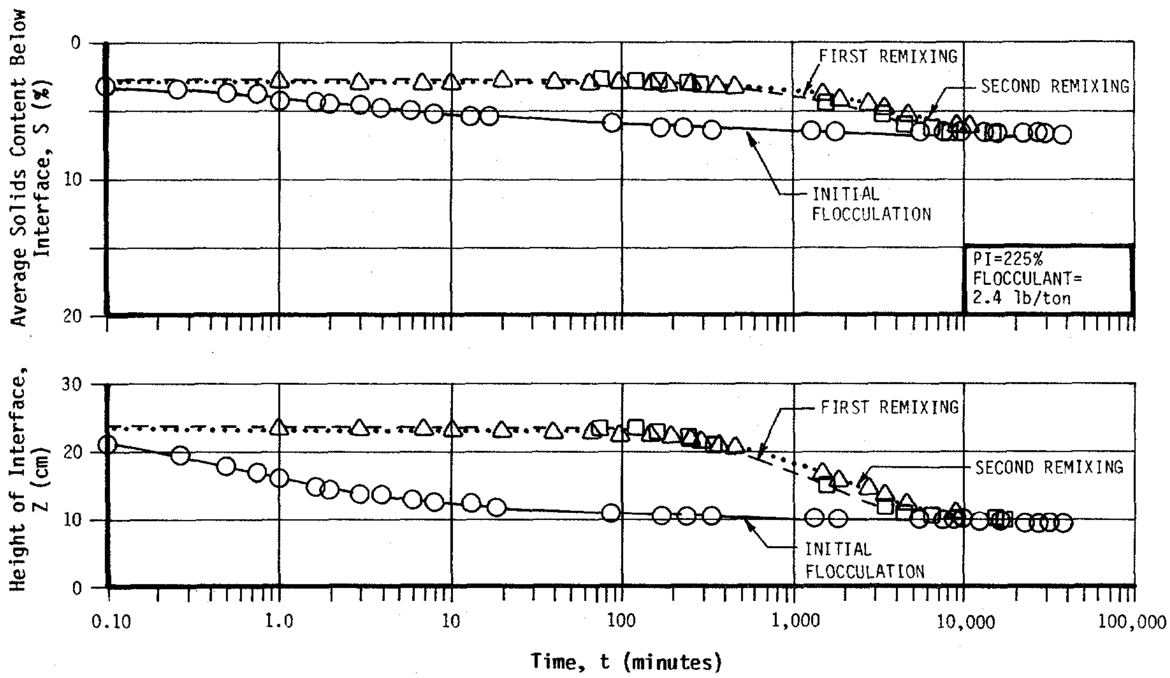


HEIGHT VS. TIME SETTLING TEST RESULTS FOR VARIOUS INITIAL SOLIDS CONTENTS FOR USSAC-ROCKLAND PHOSPHATIC CLAY AT OPTIMUM FLOCCULANT LOADING RATE

FIGURE D-6

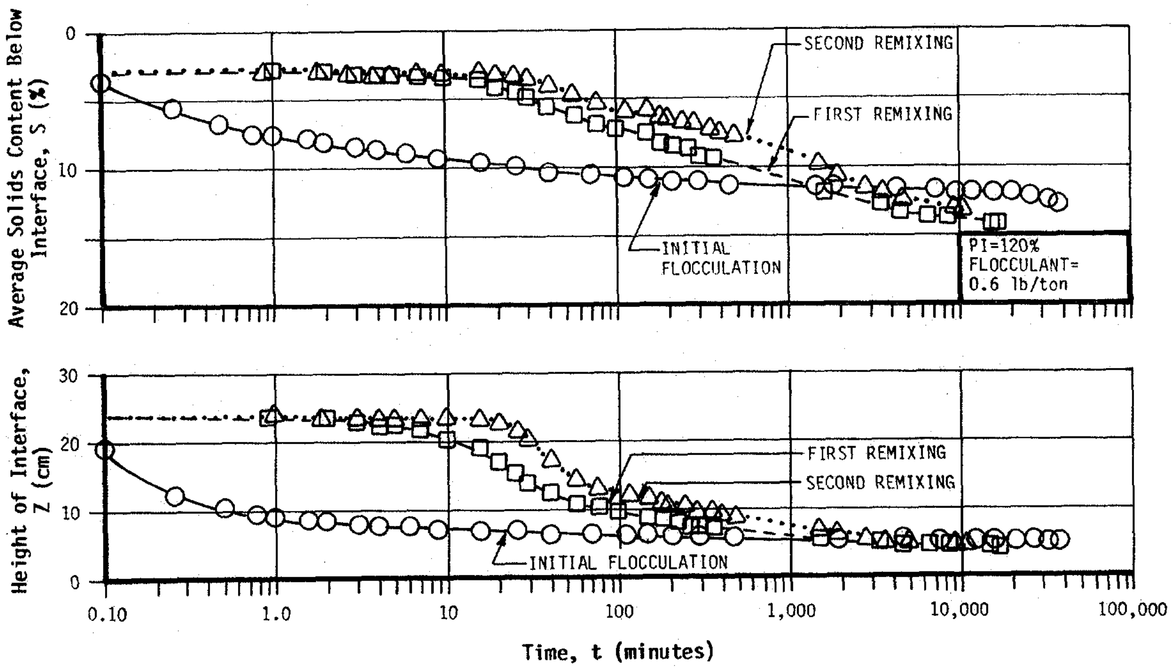
Appendix E

SOLIDS CONTENT AND HEIGHT OF INTERFACE VERSUS TIME FOR SETTLING TESTS WITH REMIXING AFTER FLOCCULATION AT 3% INITIAL SOLIDS CONTENT AND "OPTIMUM" FLOCCULANT LOADING RATE



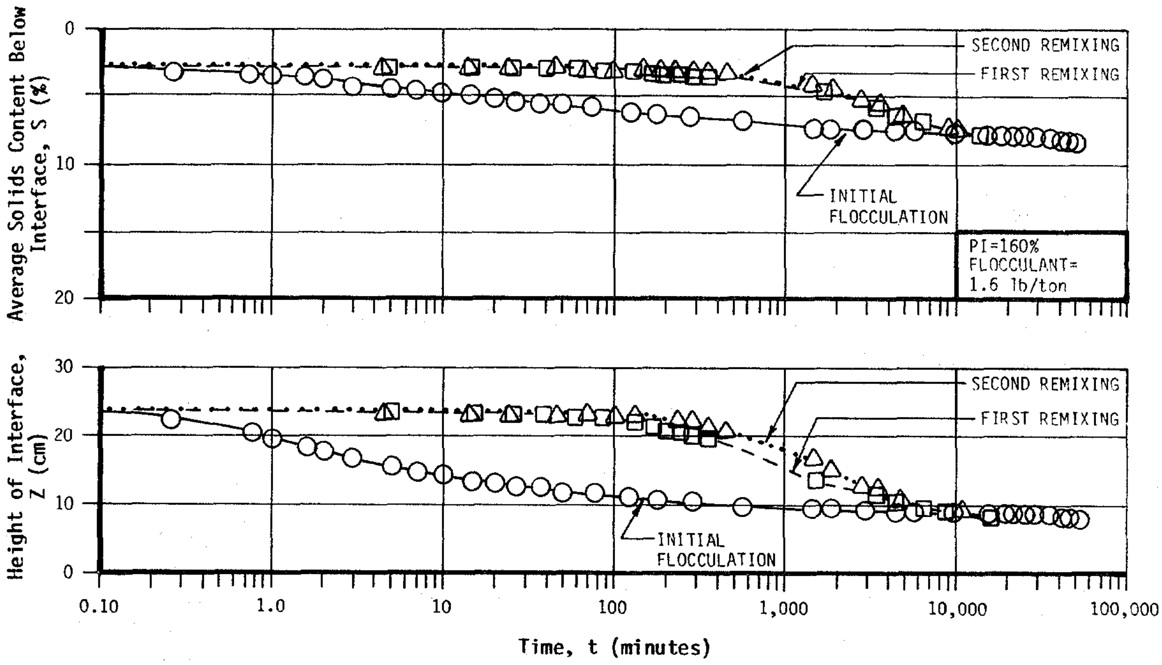
EFFECT OF MIXING AFTER FLOCCULATION ON AGRICO-SADDLE CREEK PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT AND OPTIMUM FLOCCULANT LOADING RATE

FIGURE E-1



EFFECT OF MIXING AFTER FLOCCULATION ON CF-MINING HARDEE PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT AND OPTIMUM FLOCCULENT LOADING RATE

FIGURE E-2

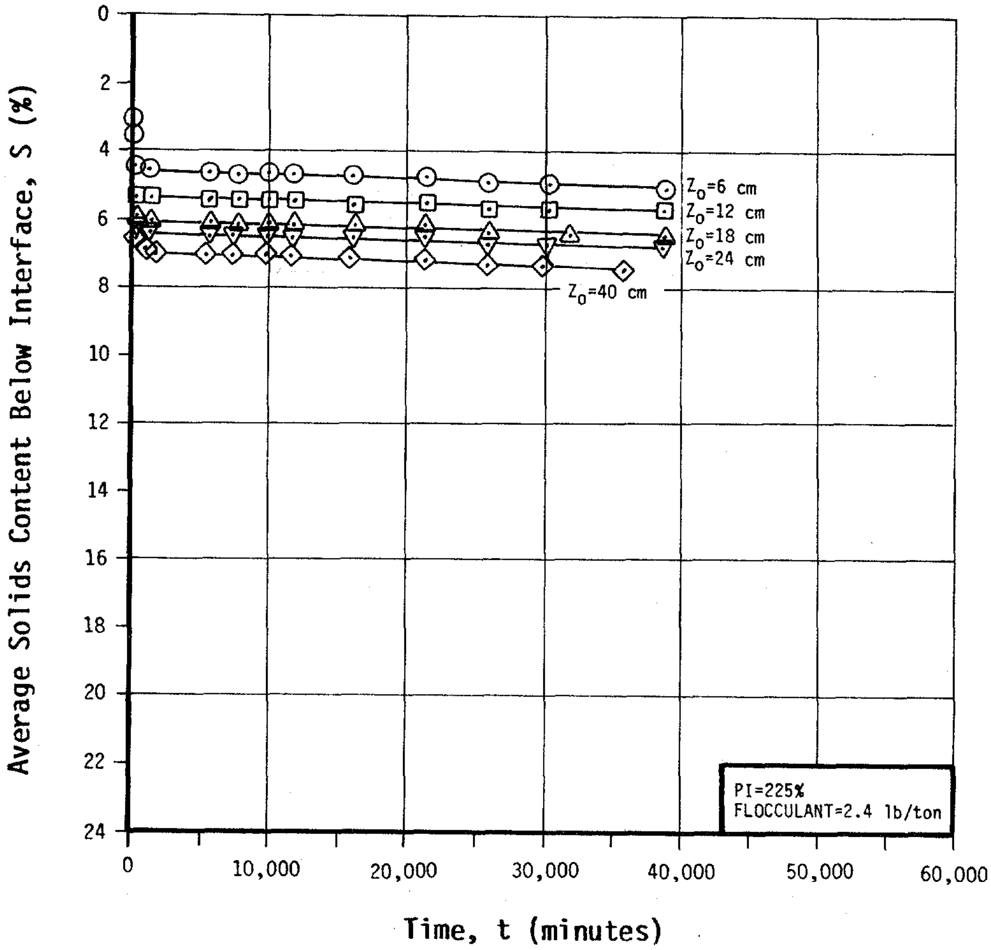


EFFECT OF MIXING AFTER FLOCCULATION ON USSAC-ROCKLAND PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT AND OPTIMUM FLOCCULANT LOADING RATE

FIGURE E-3

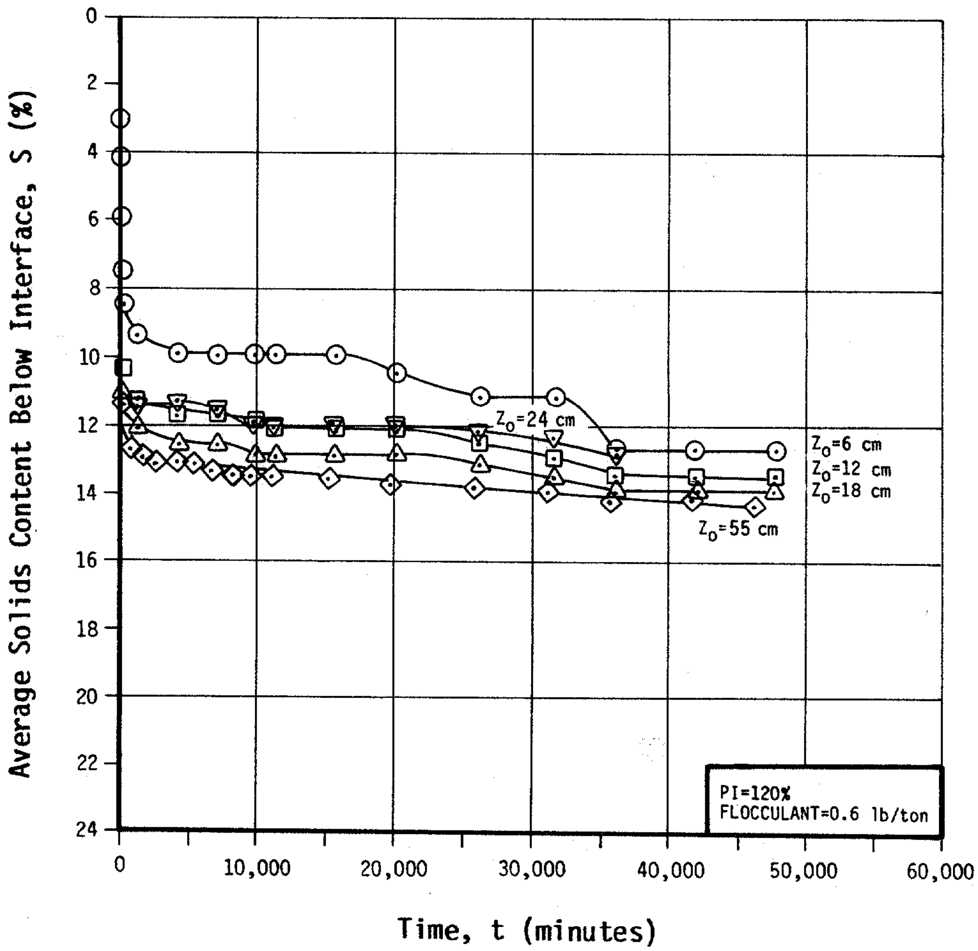
Appendix F

SOLIDS CONTENT AND HEIGHT OF INTERFACE VERSUS TIME FOR VARIABLE INITIAL HEIGHT SETTLING TESTS AT "OPTIMUM" FLOCCULANT LOADING RATE



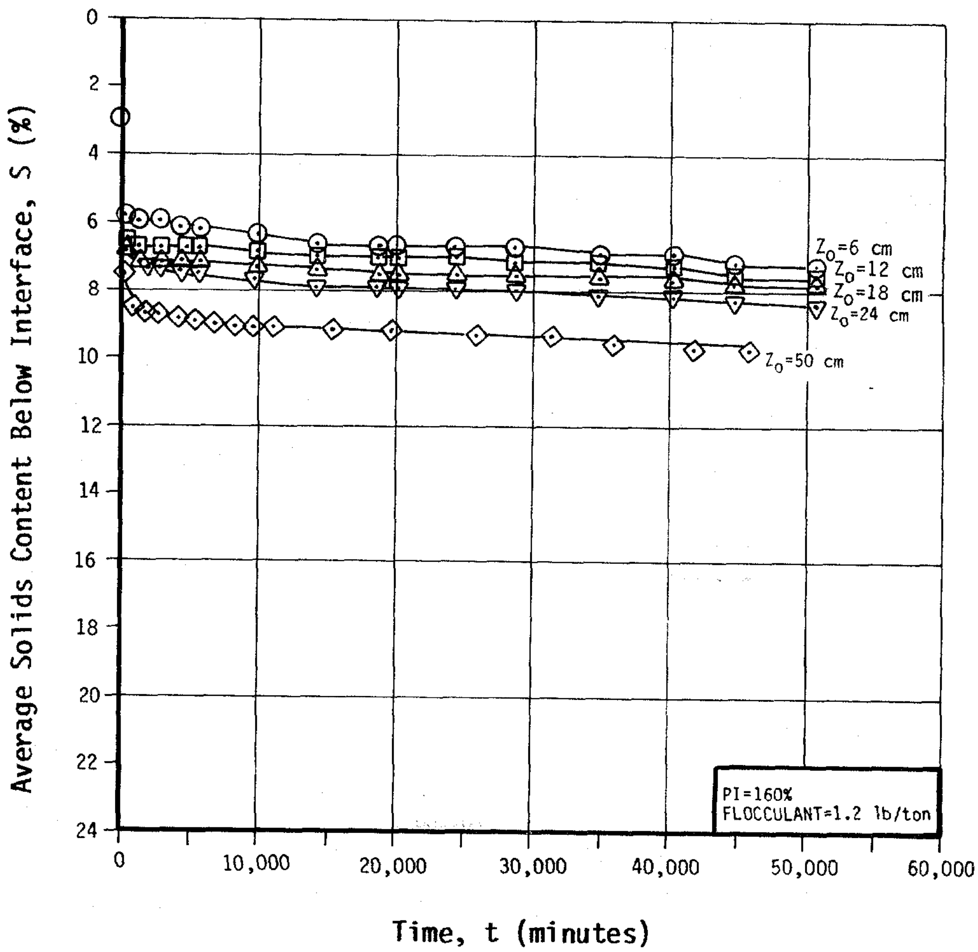
SOLIDS CONTENT VS. TIME FOR VARIOUS INITIAL SAMPLE HEIGHTS FOR AGRICO-SADDLE CREEK PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT AND OPTIMUM FLOCCULANT LOADING RATE

FIGURE F-l



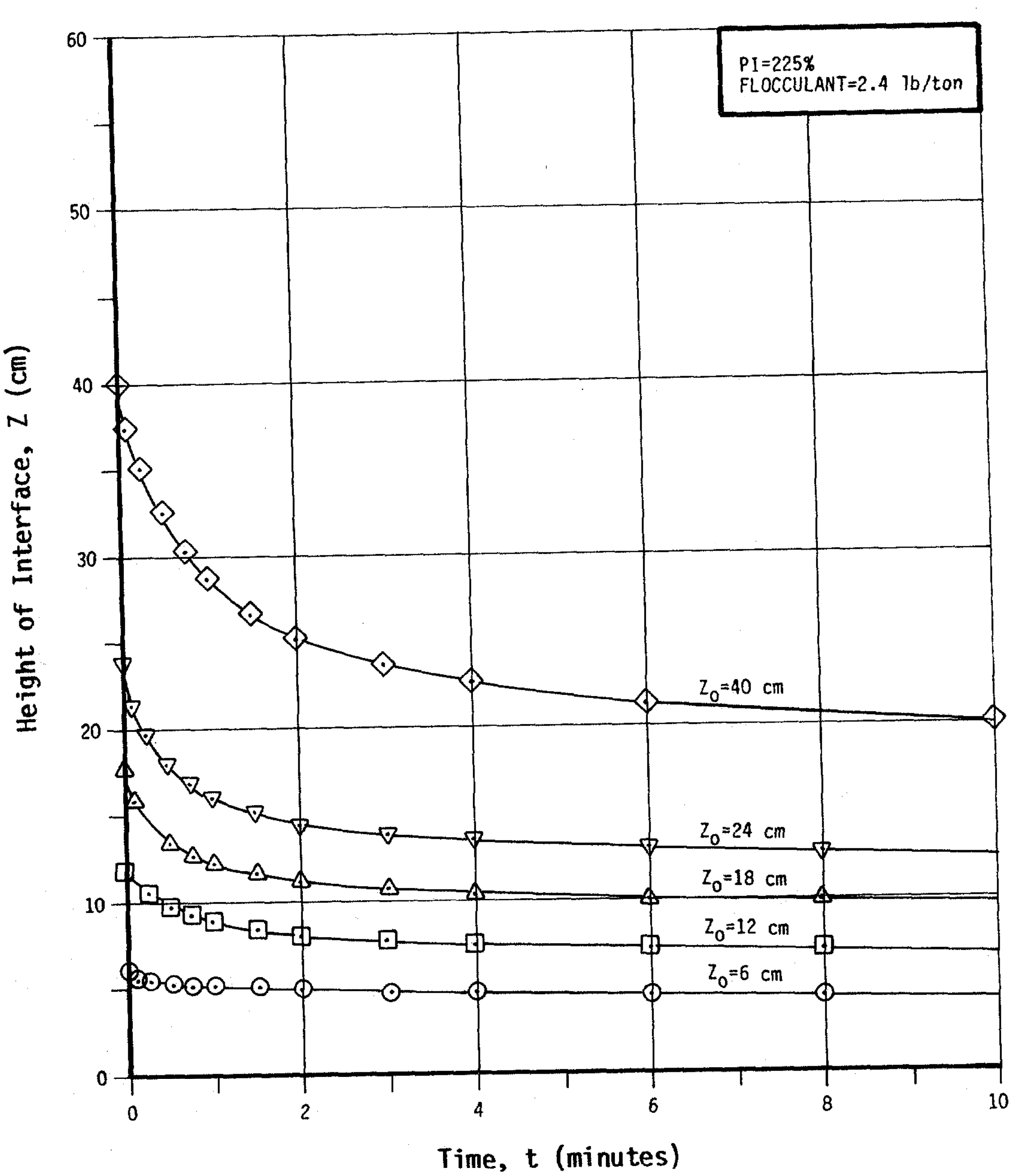
SOLIDS CONTENT VS. TIME FOR VARIOUS INITIAL SAMPLE HEIGHTS FOR CF-MINING HARDEE PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT AND OPTIMUM FLOCCULANT LOADING RATE

FIGURE F-2



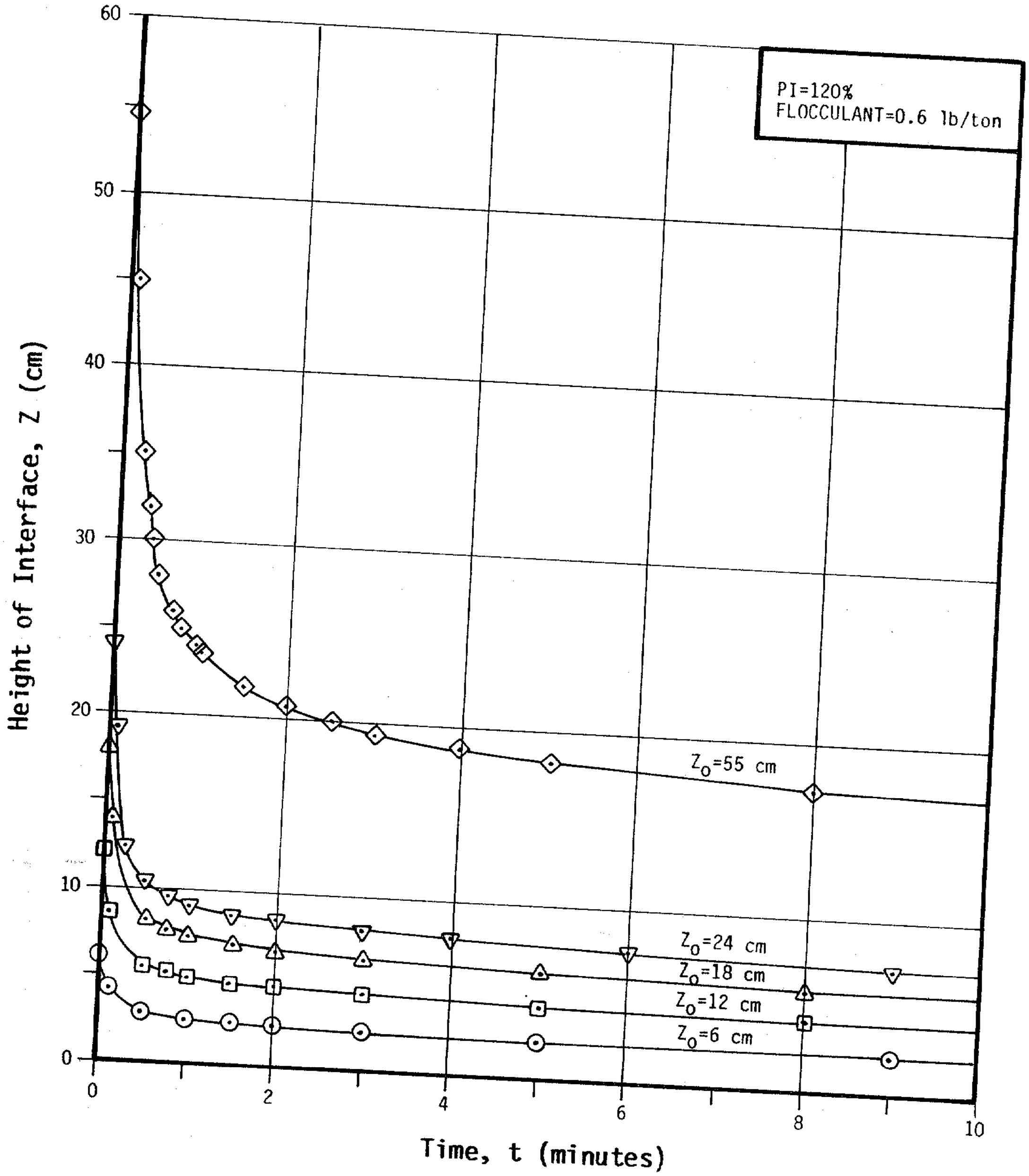
SOLIDS CONTENT VS. TIME FOR VARIOUS INITIAL SAMPLE HEIGHTS FOR USSAC-ROCKLAND PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT AND OPTIMUM FLOCCULANT LOADING RATE

FIGURE F-3



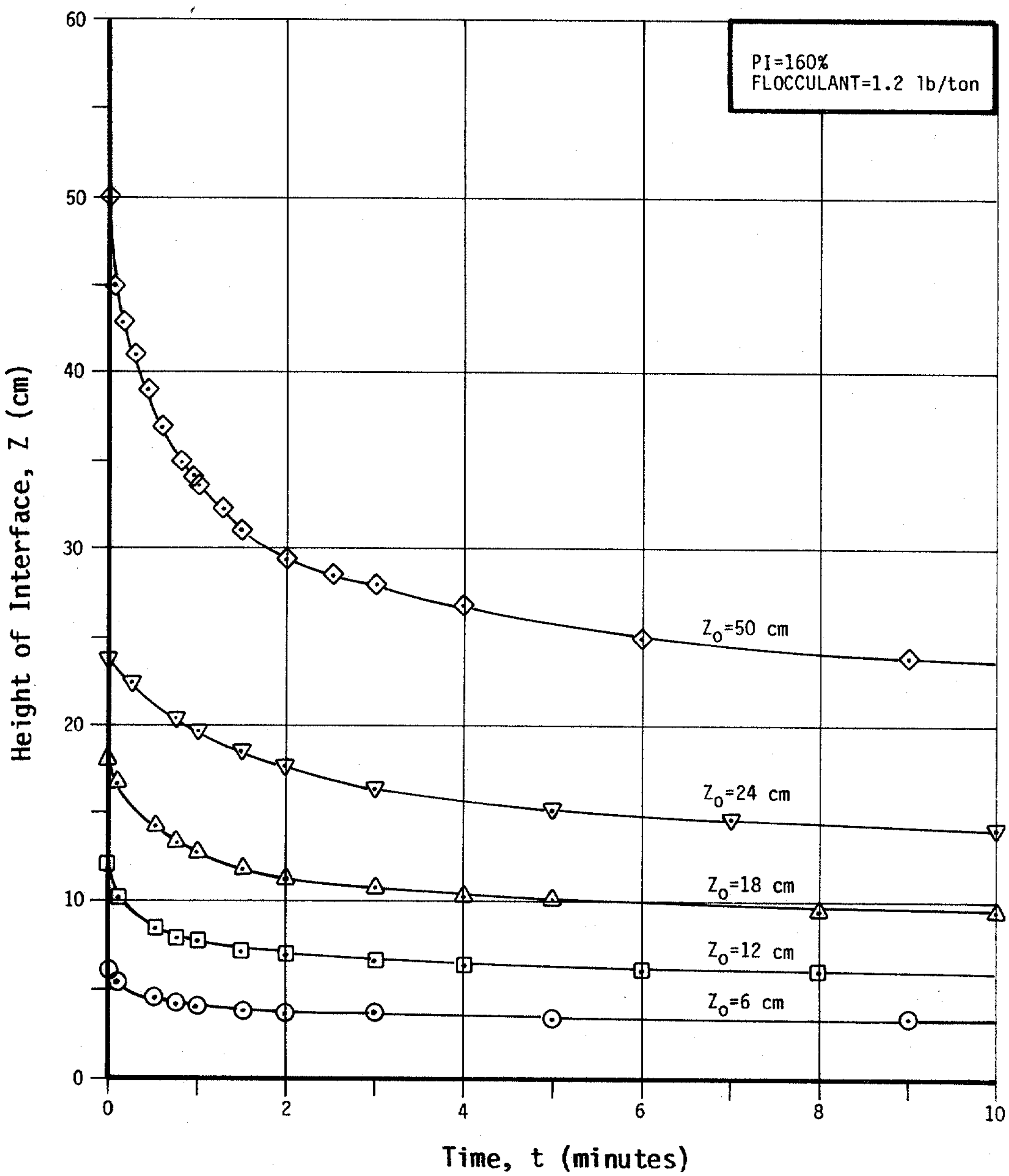
HEIGHT VS. TIME FOR VARIOUS INITIAL SAMPLE HEIGHTS FOR AGRICO-SADDLE CREEK PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT AND OPTIMUM FLOCCULANT LOADING RATE

FIGURE F-4



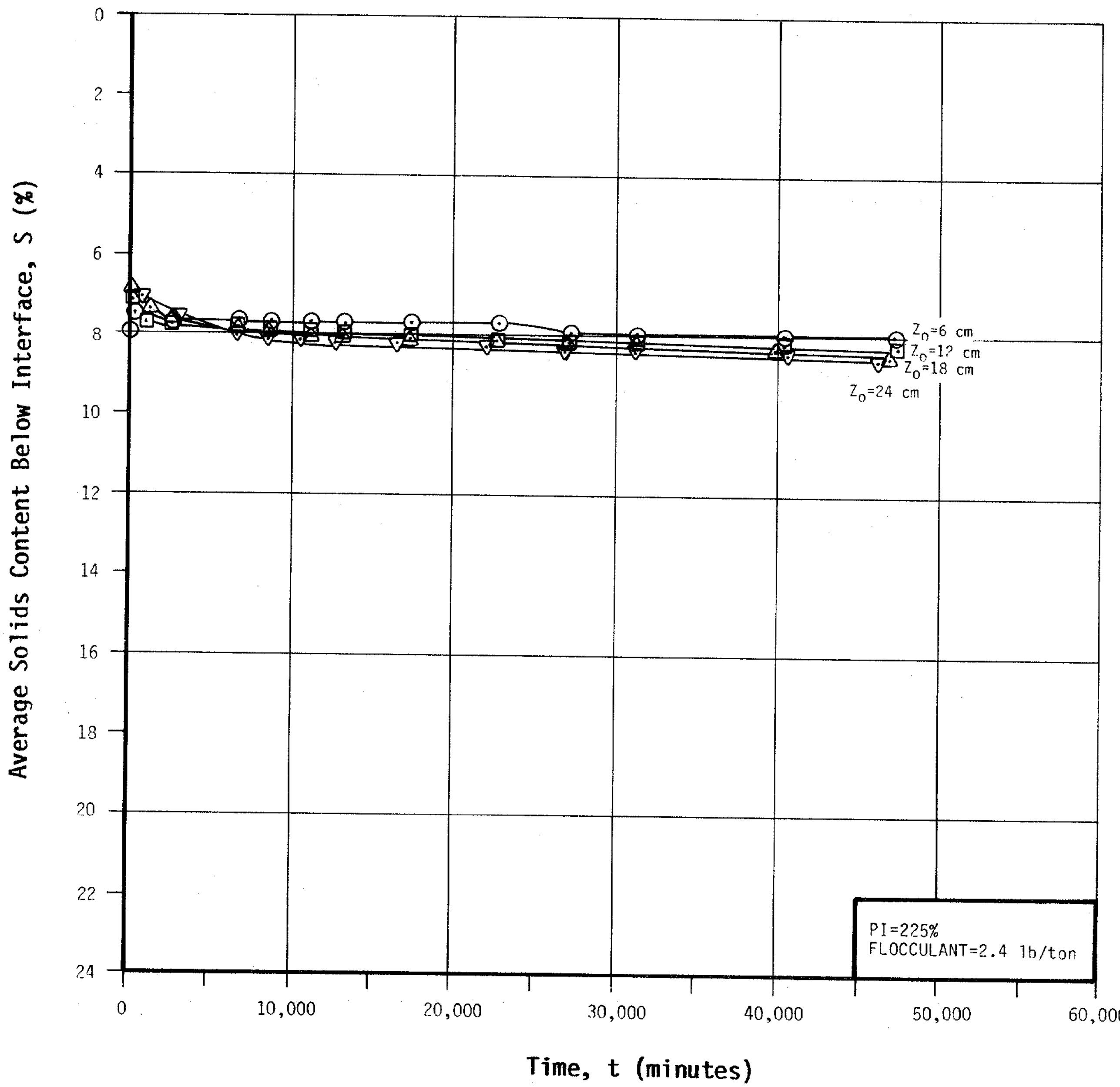
HEIGHT VS. TIME FOR VARIOUS INITIAL SAMPLE HEIGHTS FOR CF-MINING HARDEE PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT AND OPTIMUM FLOCCULANT LOADING RATE

FIGURE F-5



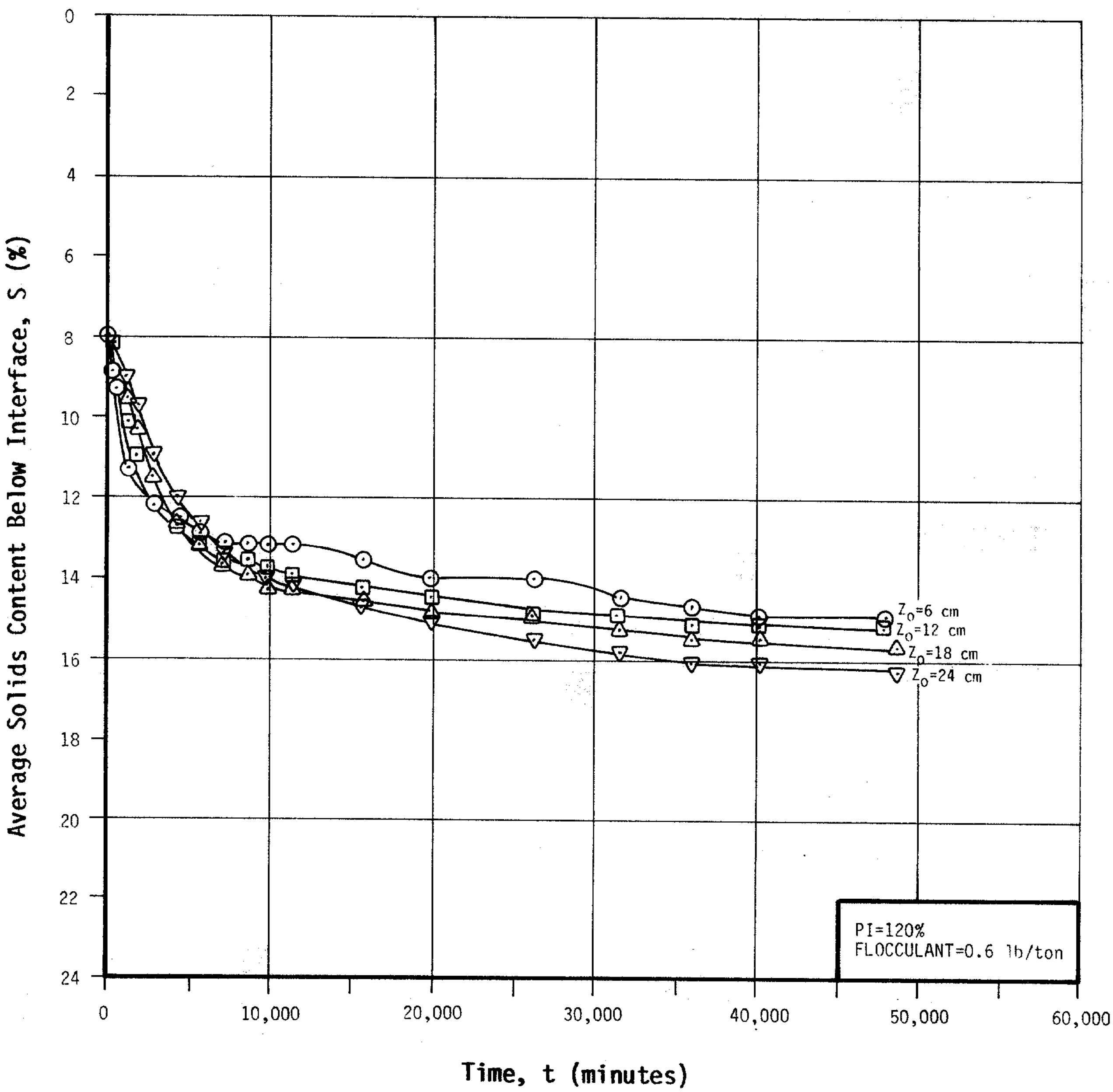
HEIGHT VS. TIME FOR VARIOUS INITIAL SAMPLE HEIGHTS FOR USSAC-ROCKLAND PHOSPHATIC CLAY AT 3% INITIAL SOLIDS CONTENT AND OPTIMUM FLOCCULANT LOADING RATE

FIGURE F-6



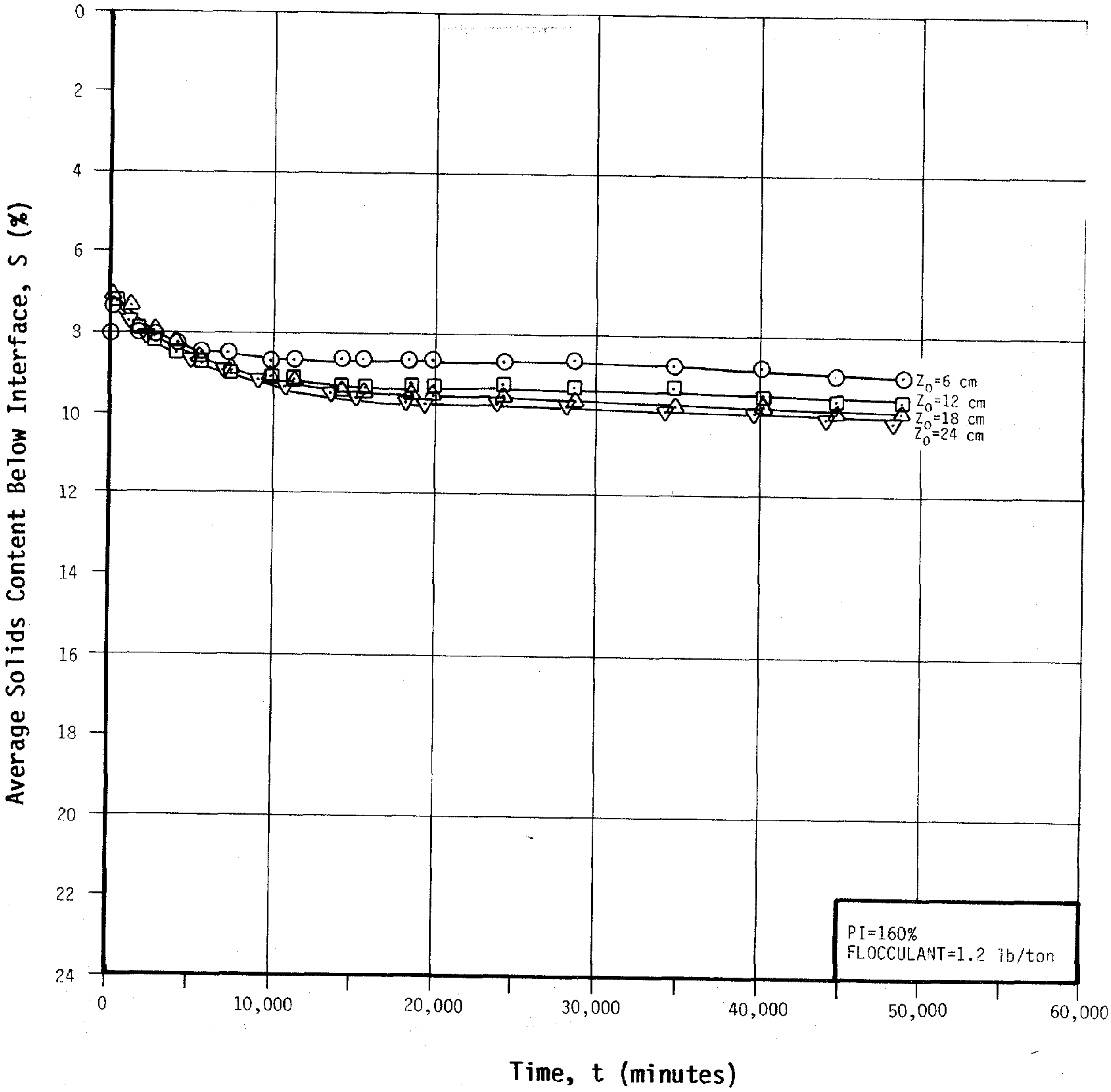
SOLIDS CONTENT VS. TIME FOR VARIOUS INITIAL SAMPLE HEIGHTS FOR AGRICO-SADDLE CREEK PHOSPHATIC CLAY AT 8% INITIAL SOLIDS CONTENT AND OPTIMUM FLOCCULANT LOADING RATE

FIGURE F-7



SOLIDS CONTENT VS. TIME FOR VARIOUS INITIAL SAMPLE HEIGHTS FOR CF-MINING HARDEE PHOSPHATIC CLAY AT 8% INITIAL SOLIDS CONTENT AND OPTIMUM FLOCCULANT LOADING RATE

FIGURE F-8



SOLIDS CONTENT VS. TIME FOR VARIOUS INITIAL SAMPLE HEIGHTS FOR USSAC-ROCKLAND PHOSPHATIC CLAY AT 8% INITIAL SOLIDS CONTENT AND OPTIMUM FLOCCULANT LOADING RATE

FIGURE F-9

Appendix G

SUMMARY OF SLURRY CONSOLIDATION TEST DATA FOR PHOSPHATIC CLAY AT "OPTIMUM" FLOCCULANT LOADING RATE

Table G-1

SLURRY CONSOLIDATION TEST DATA FOR AGRICO-SADDLE CREEK PHOSPHATIC CLAY AT "OPTIMUM" FLOCCULANT LOADING RATE

Stress $\bar{\sigma}_{vc}$ (kg/cm^2)	Void Ratio e_{100}	Void Ratio e_{50}	c_v* (cm^2/sec)	k_c* (cm/sec)	Measured Permeability e**	Measured Permeability k_m** (cm/sec)	C_α (%)
0.0013	32.7	34.9	$1.35x10^{-2}$	$2.46x10^{-3}$	-	-	-
0.0023	22.6	25.3	$6.87x10^{-5}$	$1.30x10^{-5}$	22.5	$5.59x10^{-6}$	2.71
0.0043	20.0	21.2	$7.89x10^{-5}$	$4.17x10^{-6}$	19.9	$8.21x10^{-6}$	1.75
0.0083	17.9	18.9	$2.13x10^{-4}$	$4.93x10^{-6}$	17.6	$6.31x10^{-6}$	0.99
0.016	15.8	16.7	$3.14x10^{-4}$	$3.72x10^{-6}$	15.5	$6.73x10^{-6}$	1.77
0.032	11.5	12.2	$1.38x10^{-4}$	$9.49x10^{-7}$	10.9	$3.21x10^{-6}$	1.47
0.064	9.0	9.8	$3.62x10^{-4}$	$1.05x10^{-6}$	9.1	$1.04x10^{-6}$	-
0.128	7.2	8.1	$5.12x10^{-5}$	$1.87x10^{-7}$	7.2	$3.09x10^{-7}$	-
0.250	6.9	7.1	$1.50x10^{-4}$	$3.57x10^{-8}$	6.9	$1.91x10^{-7}$	-
0.50	5.2	6.1	$4.31x10^{-4}$	$3.60x10^{-7}$	5.0	$1.67x10^{-7}$	1.31
1.00	3.9	4.5	$2.56x10^{-4}$	$8.68x10^{-8}$	3.8	$3.89x10^{-8}$	0.91
2.00	3.1	3.5	$2.67x10^{-4}$	$4.15x10^{-8}$	3.0	$2.83x10^{-8}$	1.40
4.00	2.3	2.7	$1.91x10^{-4}$	$1.57x10^{-8}$	2.3	$2.82x10^{-8}$	1.16

• Nomenclature: $\bar{\sigma}_{vc}$ = Effective vertical consolidation stress; e_{100} = Void ratio at end of primary consolidation ($\bar{U}$=100%); e_{50} = Average void ratio for load increment ($\bar{U}$=50%); c_v = Coefficient of consolidation; k_c = Calculated coefficient of permeability from c_v and compressibility for load increment; e = Void ratio; k_m = Measured coefficient of permeability at end of load increment (beyond time for $\bar{U}$=100%); C_α = Coefficient of secondary compression.

*Based on square root of time curve fitting method.
**Void ratio and coefficient of permeability shown from average of several measurements at end of load increment.

Table G-2

SLURRY CONSOLIDATION TEST DATA FOR CF MINING-HARDEE PHOSPHATIC CLAY AT "OPTIMUM" FLOCCULANT LOADING RATE

Stress $\bar{\sigma}_{vc}$ (kg/cm^2)	Void Ratio		c_v* (cm^2/sec)	k_c* (cm/sec)	Measured Permeability		C_α (%)
	e_{100}	e_{50}			e**	k_m** (cm/sec)	
0.0015	16.8	17.5	$1.13x10^{-2}$	$1.63x10^{-3}$	-	-	-
0.0025	15.2	15.7	$2.57x10^{-3}$	$1.60x10^{-4}$	14.5	$2.27x10^{-5}$	-
0.0045	13.3	13.9	$3.93x10^{-4}$	$1.39x10^{-5}$	12.3	$1.77x10^{-6}$	0.60
0.0085	-	-	-	-	10.9	$4.26x10^{-6}$	-
0.016	9.6	10.2	$1.45x10^{-4}$	$1.99x10^{-6}$	9.4	$2.56x10^{-6}$	-
0.032	8.1	8.7	$1.59x10^{-4}$	$1.26x10^{-6}$	7.8	$2.72x10^{-6}$	-
0.064	6.6	7.2	$3.28x10^{-4}$	$1.31x10^{-6}$	6.3	$6.31x10^{-7}$	1.56
0.128	5.3	5.8	$2.12x10^{-4}$	$5.47x10^{-7}$	5.1	$2.91x10^{-7}$	1.75
0.250	-	-	-	-	4.7	$1.71x10^{-7}$	-
0.50	3.6	4.2	$1.66x10^{-4}$	$1.30x10^{-7}$	3.5	$7.27x10^{-8}$	0.83
1.00	2.8	3.2	$1.28x10^{-4}$	$3.98x10^{-8}$	2.8	$6.33x10^{-8}$	0.97
2.00	2.3	2.5	$1.21x10^{-4}$	$1.54x10^{-8}$	2.3	$1.86x10^{-8}$	0.66
4.00	1.9	2.1	$9.51x10^{-5}$	$5.72x10^{-9}$	1.8	$1.64x10^{-8}$	1.07

• Nomenclature: $\bar{\sigma}_{vc}$ = Effective vertical consolidation stress; e_{100} = Void ratio at end of primary consolidation ($\bar{U}$=100%); e_{50} = Average void ratio for load increment ($\bar{U}$=50%); c_v = Coefficient of consolidation; k_c = Calculated coefficient of permeability from c_v and compressibility for load increment; e = Void ratio; k_m = Measured coefficient of permeability at end of load increment (beyond time for $\bar{U}$=100%); C_α = Coefficient of secondary compression.

*Based on square root of time curve fitting method.
**Void ratio and coefficient of permeability shown from average of several measurements at end of load increment.

Table G-3

SLURRY CONSOLIDATION TEST DATA FOR USSAC-ROCKLAND PHOSPHATIC CLAY AT "OPTIMUM" FLOCCULANT LOADING RATE

Stress $\bar{\sigma}_{vc}$ (kg/cm^2)	Void Ratio e_{100}	Void Ratio e_{50}	c_v* (cm^2/sec)	k_c* (cm/sec)	Measured Permeability e**	Measured Permeability k_m** (cm/sec)	C_α (%)
0.0014	26.6	27.2	$2.85\text{x}10^{-2}$	$2.57\text{x}10^{-3}$	-	-	-
0.0024	22.8	24.3	$9.73\text{x}10^{-4}$	$1.11\text{x}10^{-4}$	22.1	$9.88\text{x}10^{-6}$	2.38
0.0044	20.5	21.2	$8.59\text{x}10^{-4}$	$2.63\text{x}10^{-5}$	19.6	$3.68\text{x}10^{-5}$	-
0.0084	17.4	18.4	$3.26\text{x}10^{-4}$	$7.84\text{x}10^{-6}$	16.7	$1.01\text{x}10^{-5}$	1.69
0.016	13.9	15.3	$4.03\text{x}10^{-4}$	$8.13\text{x}10^{-6}$	13.3	$6.31\text{x}10^{-6}$	-
0.032	10.6	11.9	$2.23\text{x}10^{-4}$	$2.55\text{x}10^{-6}$	10.4	$4.40\text{x}10^{-6}$	2.51
0.064	8.6	9.5	$5.65\text{x}10^{-4}$	$2.72\text{x}10^{-6}$	8.1	$2.42\text{x}10^{-6}$	-
0.128	6.6	7.3	$3.89\text{x}10^{-4}$	$1.25\text{x}10^{-6}$	6.4	$6.72\text{x}10^{-7}$	1.41
0.250	5.5	5.9	$1.72\text{x}10^{-4}$	$1.71\text{x}10^{-7}$	5.4	$2.45\text{x}10^{-7}$	0.37
0.50	4.4	4.9	$1.95\text{x}10^{-4}$	$1.17\text{x}10^{-7}$	4.3	$1.03\text{x}10^{-7}$	0.99
1.00	3.5	3.9	$1.60\text{x}10^{-4}$	$4.98\text{x}10^{-8}$	3.4	$7.61\text{x}10^{-8}$	1.51
2.00	2.8	3.1	$1.30\text{x}10^{-4}$	$1.73\text{x}10^{-8}$	2.8	$3.78\text{x}10^{-8}$	1.10
4.00	2.4	2.6	$1.41\text{x}10^{-4}$	$7.78\text{x}10^{-9}$	2.3	$2.41\text{x}10^{-8}$	1.06

• Nomenclature: $\bar{\sigma}_{vc}$ = Effective vertical consolidation stress; e_{100} = Void ratio at end of primary consolidation ($\bar{U}$=100%); e_{50} = Average void ratio for load increment ($\bar{U}$=50%); c_v = Coefficient of consolidation; k_c = Calculated coefficient of permeability from c_v and compressibility for load increment; e = Void ratio; k_m = Measured coefficient of permeability at end of load increment (beyond time for $\bar{U}$=100%); C_α = Coefficient of secondary compression.

*Based on square root of time curve fitting method.
**Void ratio and coefficient of permeability shown from average of several measurements at end of load increment.