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STABILIZATION OF PHOSPHATIC CLAY WITH LIME COLUMNS

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STABILIZATION OF PHOSPHATIC CLAY WITH LIME COLUMNS

FINAL REPORT

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Techniques have been developed to drain, crust and reclaim phosphatic clay settling areas, but construction of buildings on these lands remains problematic, because the clays just a few feet below the crust are too soft, too weak, and too compressible. Because of this, cities in the area have had to develop and grow around mined-out areas, bypassing potentially valuable real estate in the process. From FIPR's perspective, there is a need to develop economical and practical techniques to reclaim these areas to a level at which the land can be, utilized for a broad range of purposes, such as suburban housing or light commercial duty.

The lime column method has been used in other countries of the world (chiefly in the Scandinavian countries) to provide additional bearing capacity and reduced settlements for soft clays. Lime columns are constructed in situ by intimate mixing of clay and finely pulverized unhydrated lime (CaO). A drilling apparatus is augured into the ground to the desired depth, reversed, and as the rod is slowly retracted, hydrated lime is ejected into the clay by compressed air through a hollow rod in the auger. The blades turn to mix the lime with the wet clay as the rods are extracted, leaving behind a column of lime/clay mix which has reduced plasticity, increased permeability, lower water content through hydration and pozzolanic reaction, and much higher strength characteristics. This method might be suitable for the stabilization of phosphatic clays.

The degree to which lime columns might be used in central Florida is affected by economic factors as well as physical parameters, such as moisture content of the untreated clay, mineralogy of the clay, and percentage of lime added. For lime columns to be economically. practical, world-wide experience has shown that only about ten percent of the volume (or area) of clay beneath a building or structures can be treated. If more than ten percent is treated, costs for lime columns are not competitive with costs for other methods of foundation treatment. About one-third of the cost is in materials and two-thirds is capital, maintenance and repairs of equipment. Because economics dictate that only ten percent of the soil is treated, and because the whole load of the structure is carried by the columns, it is then necessary that the treated clay have at least a soil modulus 100 times that of the untreated clay so that the magnitude of settlement is reduced to one-tenth or less. This would mean, for example, that a settlement of 12 inches for untreated clay would be recued to 1.2 inches with lime columns.

Regarding the physical parameters, the initial condition of the clay pond is of great importance to the effectiveness of lime columns. The untreated clay cannot be so soft that (1) a drilling rig cannot be supported by the surface; (2) the lime has a small effect on the clay because of the dilution effect of the water; or (3) a change in the water table (due, for instance, to local drainage or drought) would cause the clay surface to drop, thereby leaving the building suspended in mid-air and imposing large negative friction on the lime columns, perhaps failing them. For phosphatic clay, this constraint means that the water table in the pond must have been lowered more than five feet below the present surface at some point in the past, or that an equivalent surcharge has been in place for awhile, such that the solids content of the untreated clay is above 40%.

Phosphatic clays at about 40% solids content are generally near the liquid limit and have a strength of at least 40 psf. Past experience in Scandinavia has shown that lime columns are not practical for clays with initial strengths lower than 49 psf.

If the above conditions are met, then the settlement of a typical one- or two-story home would be about one foot on untreated clay, which is unacceptable, and about one inch on lime columns, which is within tolerable limits.

There is an additional benefit which is provided if the permeability of the lime columns is 10 to 100 times that of the untreated clay. The columns will then act as very efficient drains and allow the small settlement of one inch to occur in a few months instead of a few years. This is important because most of the load is applied during the early stages of construction (the pad of soil plus the slab or flooring) so that by the end of construction, almost no more settlement will occur.

In order to evaluate the feasibility of using the lime column method as a stabilization technique within the above-mentioned economic and physical parameters, FIPR granted a one-year study to Bromwell & Carrier, Inc.

The major objective of this project was to investigate in a laboratory setting the engineering characteristics of phosphatic waste clay mixed with various amounts of lime, lime and gypsum, and cement, and to relate those characteristics to the practical use of lime columns as a soil stabilization technique for structural foundations. Economic and physical constraints of lime columns were to be considered in choosing the initial condition of the clays prior to testing, as well as the overall testing scheme.

For the study, waste phosphatic clay was sampled from three clay settling areas with low, medium, and high plasticity clays (PI = 113-205). The clays were dried out to various initial moisture contents ranging from about 100 to 200 percent and mixed with up to 30 percent (dry weight basis) unhydrated lime, cement, or a combination one-third lime and two-thirds commercially available gypsum. Sand was added to some clays at 1:1 and 2:1 sand/clay ratios. Control clay samples with no additives were also prepared. In all, 136 different mix designs were prepared.

The above soil samples were compacted into containers and allowed to cure underwater for a period of 360 days. Samples were tested at various intervals of curing time for shear strength, pH, moisture content, plasticity, compressibility, and permeability. The laboratory study involved over 4,500 strength readings, 1,500 moisture contents, 1,200 pH measurements, 70 Atterberg limits (plasticity), 26 permeabilities and 18 consolidation tests. In addition, x-ray diffraction analysis was done on samples of clays and admixtures.

The results of the lab tests indicate that nearly all the above-mentioned criteria can be met with the treated clay. Strength increased both immediately and with time,from ten to 100 or more times the strength of the untreated clay. The magnitude of strength increase was dependent on the initial solids content of the clay and the percent of lime, lime and gypsum, or cement added. Deformations due to loading were very small after only one month of curing, particularly within the range of the pressures imposed by a one- to two-story building (i.e., below the "apparent" preconsolidation pressure). Permeability of the clays was increased an average of one order of magnitude. The pH of the clay was raised to around 12 when mixed, but leaching and other environmental concerns do not appear to be a problem, due to the low permeability of untreated clay surrounding the columns.

The investigators recommend field testing of this method. It is believed that the laboratory data is encouraging and field data will produce firm information about feasibility of applying the lime column method for stabilization of clay settling areas for construction purposes.

ABSTRACT

The Florida Institute of Phosphate Research in 1986 funded a one-year laboratory study to investigate the applicability of the lime column method as a stabilization technique for many of Central Florida's waste phosphate clay deposits. The lime column method of stabilization has been used extensively in Europe and Japan, where soft clays need to be treated to provide bearing strength for residential and light industrial loads. The method involves in situ mixing of unslaked lime with clay to form a 20-inch diameter column of clay/lime mixture.

For the study, waste phosphatic clay was sampled from three clay settling areas with low, medium, and high plasticity clays (PI = 113-205). The clays were dried out to various initial moisture contents ranging from about 100 to 200 percent and mixed with up to 30 percent (dry weight basis) unhydrated lime, cement, or a combination 1/3 lime and 2/3 commercially available gypsum. Sand was added to some clays at 1:1 and 2:1 sand/clay ratios. Control clay samples with no additives were also prepared. In all, 136 different mix designs were prepared.

The above soil samples were compacted into containers and allowed to cure underwater for a period of 360 days. Samples were tested at various intervals of curing time for shear strength, pH, moisture content, plasticity, compressibility, and permeability. The laboratory study involved over 4500 strength readings, 1500 moisture contents, 1200 pH measurements, 70 Atterberg limits (plasticity), 26 permeabilities and 18 consolidation tests. In addition, x-ray diffraction analysis was done on samples of clays and admixtures.

Results of the strength tests indicate that when phosphatic clays are mixed with lime, strength is increased initially due to hydration and with time due to pozzolanic chemical reactions. Ultimate strength gains (1 year) ranged from 20 to 200 times the initial strength of the clay. Similar strength gains were measured on clay mixed with both lime and gypsum, and clay mixed with portland cement, while no strength gain was measured on control samples. Other results of the lab study are as follows: plasticity of the mixes was significantly reduced; deformations as measured by one-dimensional consolidation tests were reduced to one-tenth or less; and permeability was increased, about one order of magnitude.

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Section 1

INTRODUCTION

The phosphate mining industry has created over 75,000 acres of phosphatic clay ponds in Central Florida, with an additional 3500 acres added annually. Techniques have been developed to drain, crust and reclaim these areas, but construction of buildings on these lands remains problematic, because the clays just a few feet below the crust are too soft, too weak, and too compressible. Because of this, cities in the area have had to develop and grow around mined-out areas, bypassing potentially valuable real estate in the process. For this reason, a need exists to develop economical and practical techniques to reclaim these areas to a level at which the land can be utilized for a broad range of purposes, such as suburban housing or light commercial duty.

The lime column method has been used in other countries of the world (chiefly in the Scandinavian countries) to provide additional bearing capacity and reduced settlements for soft clays, and may be suitable for use with phosphatic waste clay. Lime columns are constructed in situ by intimate mixing of clay and finely pulverized unhydrated lime (CaO). A drilling apparatus is augured into the ground to the desired depth, reversed, and as the rod is slowly retracted, hydrated lime is ejected into the clay by compressed air through a hollow rod in the auger. The blades turn to mix the lime with the wet clay as the rods are extracted, leaving behind a column of lime/clay mix which has reduced plasticity, increased permeability, lower water content through hydration and pozzolanic reaction, and much higher strength characteristics.

1.1 PROJECT OBJECTIVES

The objective of this project is to investigate in a laboratory setting the engineering characteristics of phosphatic waste clay mixed with various amounts of lime, lime and gypsum, and cement, and to relate those characteristics to the practical use of lime columns as a soil stabilization technique for structural foundations. Economic and physical constraints of lime columns were considered in choosing the initial condition of the clays prior to testing, as well as the overall testing scheme.

Additionally, a literature search was conducted and a bibliography made for aspects related to lime columns and phosphatic waste clay.

1.2 ECONOMIC CONSTRAINTS OF LIME COLUMNS

The degree to which lime columns might be used in Central Florida is affected by economic factors as well as physical parameters, such as moisture content of the untreated clay (or solids content (Sc), where Sc = 1 / [1 + moisture content] *100%), mineralogy of the clay, and percentage of lime added. For lime columns to be economically practical, world-wide experience has shown that only about 10 percent of the volume (or area) of clay beneath a building or structures can be treated. If more than 10 percent is treated, costs for lime columns are not competitive with costs for other methods of foundation treatment. About 1/3 of the cost is in materials (lime and gypsum) and 2/3 of the cost is capital, maintenance and repairs of equipment.

Because economics dictate that only 10 percent of the soil is treated, and because the whole load of the structure is carried by the columns, it is then necessary that the treated clay have at least a soil modulus 100 times that of the untreated clay so that the magnitude of settlement is reduced to one-tenth or less. This would mean, for example, that a settlement of 12 inches for untreated clay would be reduced to 1.2 inches with lime columns.

1.3 PHYSICAL CONSTRAINTS ON LIME COLUMN PERFORMANCE

The initial condition of the clay pond is of great importance to the effectiveness of lime columns. The untreated clay cannot be so soft that (1) a drilling rig cannot be supported by the surface; (2) the lime has a small effect on the clay because of the dilution effect of the water; or (3) a change in the water table (due, for instance, to local drainage or drought) would cause the clay surface to drop, thereby leaving the building suspended in mid-air and imposing large negative friction on the lime columns, perhaps failing them. For phosphatic clay, this constraint means that the water table in the pond must have been lowered more than five feet below the present surface at some point in the past, or that an equivalent surcharge has been in place for awhile, such that the solids content of the untreated clay is above 40%.

Phosphatic clays at about 40% solids content are generally near the liquid limit and have a strength of at least 40 psf. Past experience in Scandinavia has shown that lime columns are not practical for clays with initial strengths lower than 40 psf.

If the above conditions are met, then the settlement of a typical one- or two-story home would be about 1 foot on untreated clay, which is unacceptable, and about 1 inch on lime columns, which is within tolerable limits. Design calculations for lime columns on a “typical” phosphatic clay profile will be presented in a later portion of this report.

There is an additional benefit which is provided if the permeability of the lime columns is 10 to 100 times that of the untreated clay. The columns will then act as very efficient drains and allow the small settlement of 1 inch to occur in a few months instead of a few years. This is important because most of the load is applied during the early stages of construction (the pad of soil plus the slab or flooring) so that by the end of construction, almost no more settlement will occur.

1.4 RESULTS OF TESTING PROGRAM

The results of our lab tests indicate that nearly all the above-mentioned criteria can be met with the treated clay. Strength increased both immediately and with time, from 10 to 100 or more times the strength of the untreated clay. The magnitude of strength increase was dependent on the initial solids content of the clay and the percent of lime, lime and gypsum, or cement added. Deformations due to loading were very small after only 1 month of curing, particularly within the range of the pressures imposed by a one- to two-story building (i.e., below the “apparent” preconsolidation pressure). Permeability of the clays was increased an average of one order of magnitude. The pH of the clay was raised to around 12 when mixed, but leaching and other environmental concerns do not appear to be a problem, due to the low permeability of untreated clay surrounding the columns.

Section 2

PROJECT DESCRIPTION

The two main objectives of the project were to perform a laboratory investigation as to the engineering properties of phosphatic Wasteclay treated with lime, gypsum, and cement, and to provide a literature review of papers dealing with various topics related to the use of lime columns.

2.1 LABORATORY TESTING PROGRAM

2.1.1 Description of Equipment

The following equipment was used to mix the samples or perform laboratory experiments:

Commercial Mixer	Blakeslee Model B-20T
Grinder	no model no.
Electronic Scale	Sartorius Model U 5000 D
Laboratory Oven	Fischer ECONOTEMP 30G
pH Meter	Horizon Model 5995
Uniaxial Compression	Soiltest Model CN 700, w/ Soiltest 50 lb. load ring
Fall Cone Apparatus	Geonor A/S Model g-200
Vane Shear Device	Pilcon Engineering (no model)
Permeameter	Soiltest Model 455-300

Fixed Ring Consolidometer	Wykeham-Farrance WF-24001 (fixed arm type)
Fixed Ring Consolidometer	Karol-Warner Model 350 (pneumatic type)
Atterberg Limit Cup	Soiltest Model CL-204

2.1.2 Methodology and Procedures

The purpose of the laboratory investigation was to find the effect of unhydrated lime (CaO), cement, and a lime-gypsum mix (2/3 lime, 1/3 $CaSO_4$ gypsum) on phosphatic clays having a wide range of plasticity. Parameters which were tested were the plasticity, strength, permeability, compressibility, compaction, and pH. Laboratory controlled variables which affected the engineering properties were: (1) the initial strength of the untreated clay (as determined by the initial moisture or solids content); (2) the percentage of admixture; and (3) the time of curing.

The first phase of research began with a search of the literature and sampling of clays from different mines in the area to find three clays which represented the range of plasticity which could be encountered in Central Florida. Six clay settling areas were selected as preliminary sites, based on the plasticity indices found in the literature search. These ponds were sampled and the clay was tested for plasticity. Results are presented as follows:

Mine Area	Plasticity Index (PI)
Brewster Haynsworth D	163, 181
Amax Big Four BF-1	163
IMC Noralyn N-2	146
Mobil Nichols N-3	205, 191, 209
USS Agrichem-Rockland N-4	115, 113
Brewster Haynsworth SP-4	83

Tests were also run to measure the sensitivity of the plasticity to lime addition. It was found that the addition of 10% lime had the effect of lowering the plasticity index of the soil by 10 to 20 percent, with no apparent dependence on the initial plasticity (Figure 2.1). Another effect was to change the classification of each clay from CH (Unified Soil Classification System) or highly plastic clay, to MH-OH, or plastic silt (Figure 2.2).

From the above list, three clays with low, medium, and high plasticity were selected for the testing program based on the measured plasticity and the availability and accessibility ofthe clay for bulk sampling. The high plasticity clay (designated Clay A) was from Mobil Nichols Mine. The medium (Clay B) and low (Clay C) plasticity clays

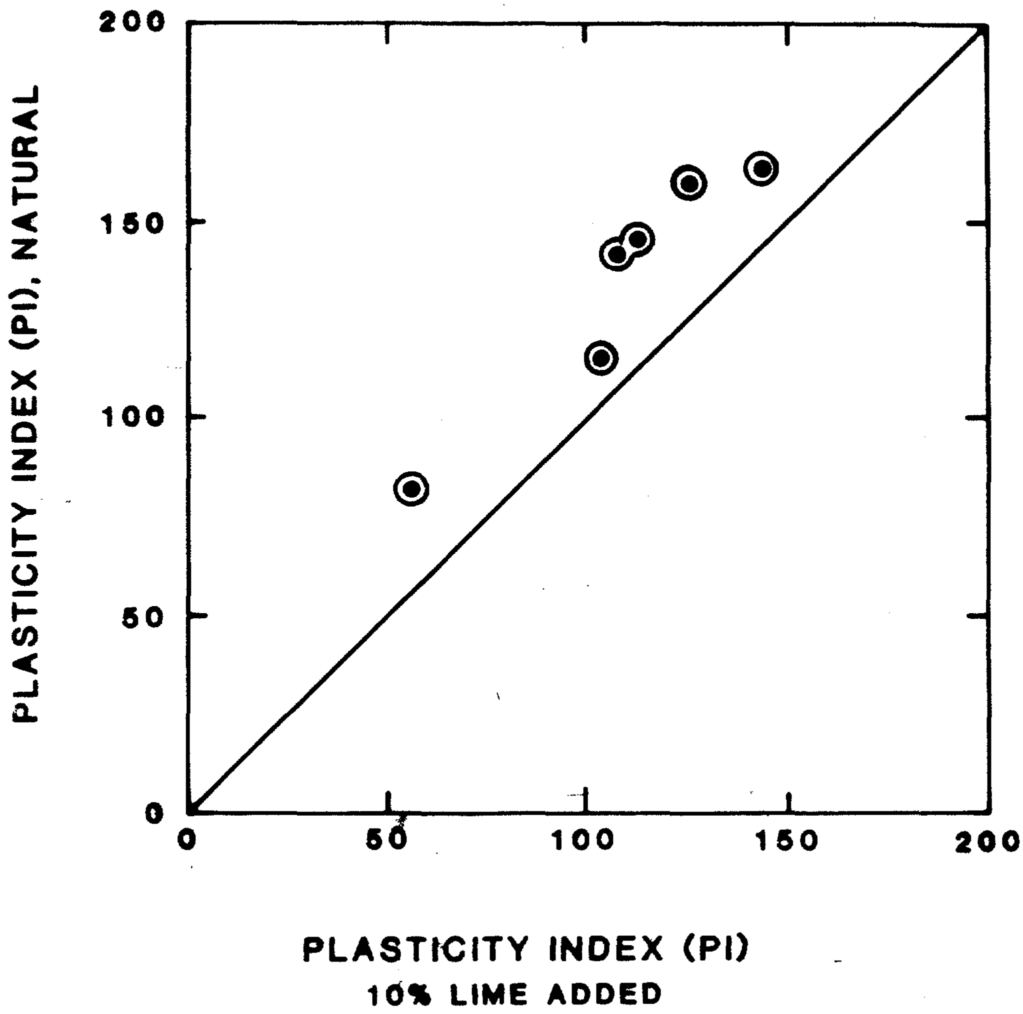

Figure 2.1 Effect of lime on the Plasticity Index of phosphatic clays.

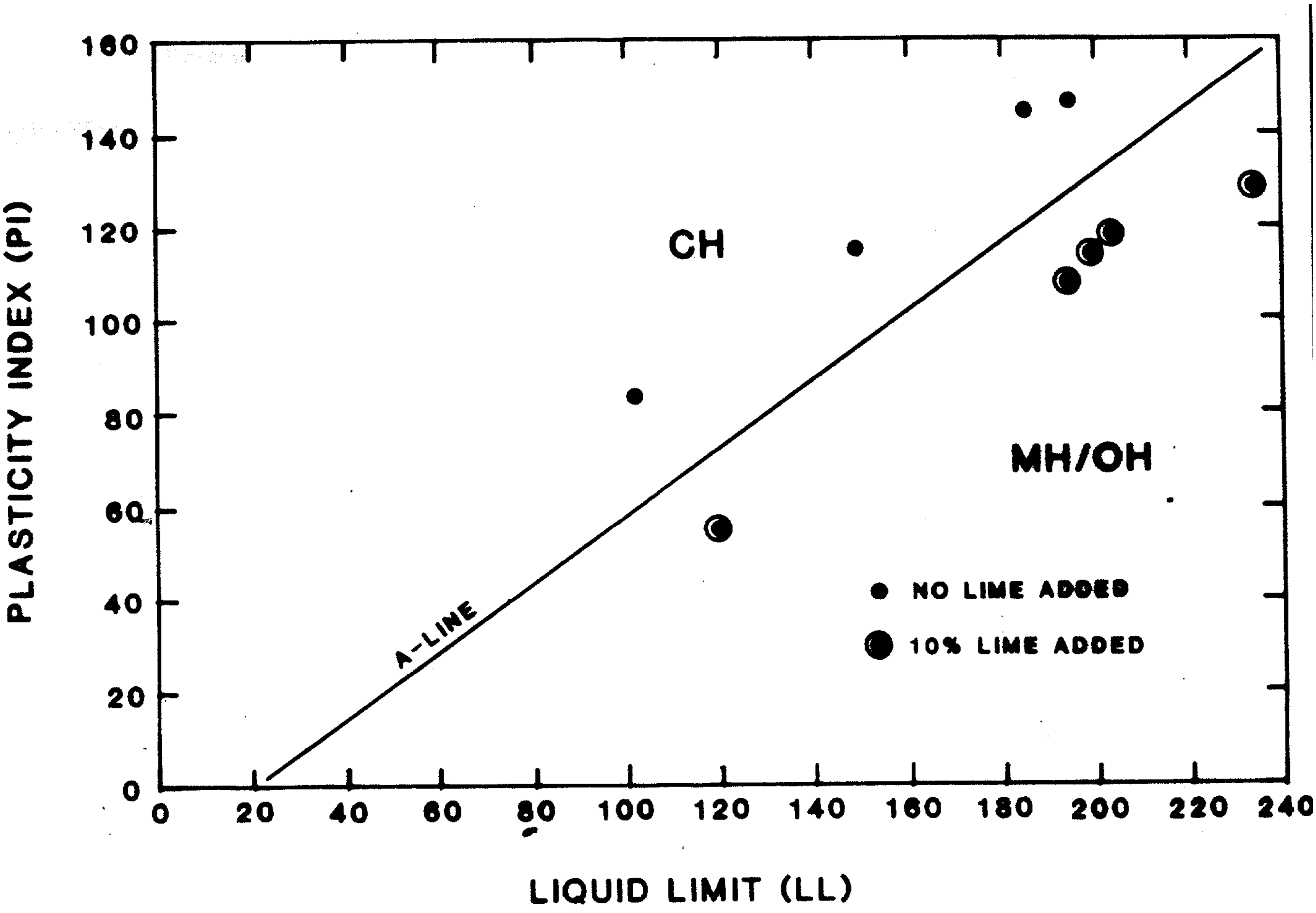

Figure 2.2 Effect of lime on the classification of phosphatic clay.

were from Brewster Haynsworth Area D and USS Agrichem Area N-4, respectively. The medium plasticity clay (Clay B from Haynsworth) was mixed with sand for Clay D (1:1 sand/clay ratio) and Clay E (2:1 sand/clay ratio).

Once these samples were chosen, a series of tests were run to classify the soils. These tests included typical geotechnical engineering tests such as percent minus the #200 sieve and specific gravity. In addition, the chemical composition of the phosphatic waste clay samples was found in the literature search.

Samples were prepared for testing at several initial clay strengths to show the change in properties of clay admixtures over a wide range of initial conditions in the field. Based on the lime columns-literature, a minimum initial strength of clay was selected as 42 psf. The moisture content for a clay with a strength of 42 psf corresponds roughly to the liquid limit of that clay, and varies from clay to clay. When the strength is below 42 psf, the clay has a high moisture content and too much lime has to be added to make the method economical. Clays were prepared at 42, 84, 167 and 250 psf strengths by air drying to the correct moisture content.

In the lab, the clay was weighed into a large bowl and mixed until most of the lumps were gone. The moisture content was checked and the amount of additives (lime, lime and gypsum, or cement) and water needed for a proper mix was calculated on a weight basis. The additives were then mixed with the water and clay for at least five minutes with a large commercial mixer.

After sitting undisturbed for another five minutes (mellowing time), the clay mix was then compacted with a wooden tamper into 12-inch long sections of 3-inch diameter PVC pipe. The maximum lift thickness allowed was 1.5 inches. Each pipe was filled with 10 inches or more with the clay/additive mixture. Consolidation and permeability samples were prepared in the same manner except the samples were compacted into 5-inch long segments of pipe to a minimum thickness of 4 inches. Again, samples for unconfined compression tests were prepared in the same manner, but 5-inch long PVC pipe segments with a diameter of 1.6 inches were used. Once compacted, all samples were stored submerged in a water bath at 72 degrees, the approximate ground temperature in Central Florida.

2.1.3 Mix Designs

The clay mixtures were prepared using clay from three different mines (plus two sand/clay mixes), at one of 4 initial strengths, and with one of nine possible admixtures. Each mix was given a designation which describes the mix in terms of the clay type, initial clay strength prior to treatment, and the percentage by weight of amendment added to the clay. The initial strength of the clay in this designation is expressed in units of kiloPascals (kPa), where 1 kPa = 20.88 psf; therefore, initial strengths of 2 ,4 ,8, and 12 kPa correspond to 42, 84, 167, and 250 psf, respectively, in English units. For example, the designation A-2-10LG stands for Clay A from Mobil, at an initial strength of 2 kiloPascals (42 psf), with 10 percent of the lime/gypsum mix added.

The majority of the strength tests were run with the fall cone penetrometer. This test apparatus, which was developed in Sweden, may be used to give a quick laboratory determination of the shear strength of a soil. In the test, it is assumed that the shear strength of the soil is inversely proportional to the penetration of the cone. Four cones of different weights and apex angles allow the test to be performed over a wide range of material strengths. However, the testing scheme was modified when it became obvious that the strengths obtained would be higher than the readability of the fall cone apparatus.

In addition to the fall cone method, strength determinations were made by the vane shear method and by the unconfined compression method for comparison purposes. After a few tests it was determined that adding sand to the samples increased the strength beyond the readability of both the fall cone and the vane shear devices. Therefore, all strength test on sand-clay mixtures with more than six percent lime were run by the unconfined compression method, for which higher strength readings were possible. Table 2.1 shows the different mixes which were tested for strength. Each mixture wastested for moisture content, strength, and pH at 0, 7, 28, 90, 180, and 360 elapsed days after preparation. Over 1500 moisture contents and strengths were measured, and over 1250 pH tests were performed during the experimentation phase of the project.

In addition to the tests mentioned above, Table 2.2 summarizes the rest of the testing scheme used for this research effort, including mixestested for consolidation, permeability, plasticity, compaction, and leaching parameters.

Tests 1, 2, 3, and 4 of Table 2.2 were run according to ASTM procedures. The procedure for the leach test was to allow the water to leach through the sample on samples which were prepared with a cotton wick at the center of the soil column.

Table 2.1

LIME COLUMN STRENGTH AND pH TEST MIXTURES

CLAY A (HIGH PLASTICITY)				
INITIAL STRENGTH (kPa):	2	4	8	12
MIXTURE				
0 % LIME	xxxx	xxxx	xxxx	xxxx
6 % LIME	xxxx	xxxx	xxxx	xxxx
10 % LIME	xxxx	xxxx	xxxx	xxxx
15 % LIME	xxxx	xxxx	xxxx	xxxx
20 % LIME	xxxx	xxxx	xxxx	xxxx
10 % LIME + GYPSUM	xxxx	xxxx	xxxx	xxxx
20 % LIME + GYPSUM	xxxx	xxxx	xxxx	xxxx
15 % CEMENT	xxxx	xxxx	xxxx	xxxx
30 % CEMENT	xxxx	xxxx	xxxx	xxxx

CLAY B (MED. PLASTICITY)				
INITIAL STRENGTH (kPa):	2	4	8	12
MIXTURE				
0 % LIME	xxxx	xxxx	xxxx	xxxx
6 % LIME	xxxx	xxxx	xxxx	xxxx
10 % LIME	xxxx	xxxx	xxxx	xxxx
15 % LIME	xxxx	xxxx	xxxx	xxxx
20 % LIME	xxxx	xxxx	xxxx	xxxx
10 % LIME + GYPSUM	xxxx	xxxx	xxxx	xxxx
20 % LIME + GYPSUM	xxxx	xxxx	xxxx	xxxx
15 % CEMENT	xxxx	xxxx	xxxx	xxxx
30 % CEMENT	xxxx	xxxx	xxxx	xxxx

CLAY C (LOW PLASTICITY)				
INITIAL STRENGTH (kPa):	2	4	8	12
MIXTURE				
0 % LIME	xxxx	xxxx	xxxx	xxxx
6 % LIME	xxxx	xxxx	xxxx	xxxx
10 % LIME	xxxx	xxxx	xxxx	xxxx
15 % LIME	xxxx	xxxx	xxxx	xxxx
20 % LIME	xxxx	xxxx	xxxx	xxxx
10 % LIME + GYPSUM	xxxx	xxxx	xxxx	xxxx
20 % LIME + GYPSUM	xxxx	xxxx	xxxx	xxxx
15 % CEMENT	xxxx	xxxx	xxxx	xxxx
30 % CEMENT	xxxx	xxxx	xxxx	xxxx

Table 2.1 (Continued)

CLAY D (1:1 S/C RATIO WITH CLAY B)

INITIAL STRENGTH (kPa): MIXTURE	2	4	8	12
0 % LIME	xxxx	xxxx	xxxx	
6 % LIME	xxxx	xxxx	xxxx	
10 % LIME	xxxx	xxxx	xxxx	
15 % LIME	xxxx	xxxx	xxxx	
20 % LIME	xxxx	xxxx	xxxx	
10 % LIME + GYPSUM	xxxx	xxxx	xxxx	
20 % LIME + GYPSUM				
15 % CEMENT	xxxx	xxxx	xxxx	
30 % CEMENT				

CLAY E (2:1 S/C RATIO WITH CLAY B)

INITIAL STRENGTH (kPa): MIXTURE	2	4	8	12
0 % LIME	xxxx			
6 % LIME	xxxx			
10 % LIME			xxxx	
15 % LIME				
20 % LIME				
10 % LIME + GYPSUM			xxxx	
20 % LIME + GYPSUM				
15 % CEMENT			xxxx	
30 % CEMENT				

Table 2.2

MIX DESIGNS FOR VARIOUS LIME COLUMN TESTS

1. CONSOLIDATION (OEDOMETER) TESTS

28-DAY AND 180 DAY TESTS, CLAYS A AND C

INITIAL STRENGTH (kPa): MIXTURE	2	4	8	12
0 % LIME	xxxx		xxxx	
6 % LIME				
10 % LIME	xxxx		xxxx	
15 % LIME				
20 % LIME	xxxx		xxxx	
10 % LIME + GYPSUM	xxxx		xxxx	
20 % LIME + GYPSUM				
15 % CEMENT	xxxx		xxxx	
30 % CEMENT				

2. PERMEABILITY TESTS

28-DAY AND 180 DAY TESTS, CLAYS A AND C

INITIAL STRENGTH (kPa): MIXTURE	2	4	8	12
0 % LIME	xxxx		xxxx	
6 % LIME				
10 % LIME	xxxx		xxxx	
15 % LIME				
20 % LIME	xxxx		xxxx	
10 % LIME + GYPSUM	xxxx		xxxx	
20 % LIME + GYPSUM				
15 % CEMENT	xxxx		xxxx	
30 % CEMENT				

3. ATTERBERG LIMIT TESTS

1, 7, AND 28-DAY TESTS, CLAYS A, B, AND C

MIXTURE	
0 % LIME	xxxx
6 % LIME	xxxx
10 % LIME	xxxx
15 % LIME	xxxx
20 % LIME	xxxx
10 % LIME + GYPSUM	xxxx
20 % LIME + GYPSUM	xxxx
15 % CEMENT	xxxx
30 % CEMENT	xxxx

Table 2.2 (Continued)

4. OPTIMUM MOISTURE CONTENT

CLAY B

MIXTURE	
0 % LIME	
6 % LIME	
10 % LIME	xxxx
15 % LIME	
20 % LIME	
10 % LIME + GYPSUM	
20 % LIME + GYPSUM	
15 % CEMENT	
30 % CEMENT	

5. LEACHING TESTS

CLAYS A, C, AND E

INITIAL STRENGTH (kPa):	2	4	8	12
MIXTURE				
0 % LIME				
6 % LIME	xxxx		xxxx	
10 % LIME	xxxx		xxxx	
15 % LIME				
20 % LIME	xxxx		xxxx	
10 % LIME + GYPSUM	xxxx		xxxx	
20 % LIME + GYPSUM				
15 % CEMENT				
30 % CEMENT				

2.2 LITERATURE REVIEW

The second major objective of the lime column project was to provide a comprehensive and up-to-date literature review on the following subjects:

1. Stabilization with Lime
2. Stabilization of Phosphatic Clay with Lime
3. The Lime Column Method

The literature review is included in the Appendix of this report.

Section 3

RESULTS AND DISCUSSION

3.1 CLAY CHARACTERISTICS

3.1.1 Physical Characteristics

Bulk samples of phosphatic clays used were obtained from waste clay ponds at three mines in the Central Florida area: the Mobil Nichols mine, the USS Agrichem Rockland mine, and the Brewster Haynsworth mine. The clays were selected based on previous engineering index properties listed in the literature (Bromwell Engineering, 1982). These engineering propertiesare presented on Table 3.1, along with values measured in our lab after sampling. Fair agreement between listed and measured physical parameters was found. The Atterberg limits, a measure of the plasticity of the clay, are within the expected range for phosphatic clay. Other physical parameters are also typical for phosphatic clay.

The amendments used in the mixes were commercially available unhydrated lime (also called quicklime), gypsum, and portland cement. The lime was pebble size and had to be finely ground in order to properly mix with the Clay. Phosphogypsum was not used as an admixture.

Table 3.1

PHYSICAL/ENGINEERING PROPERTIES AND CLASSIFICATION OF PHOSPHATIC CLAYS

Sample	Classification (USCS)	%-#200 Mesh	Atterberg Limits	Specific Gravity
Mobil Nichols (from liter.)	CH		LL=184 PL= 33 PI=151	2.6
(measured) Area N-3	CH	99.2	LL=186 PL= 42 PI=205	2.68
IMC Haynsworth D (measured)	CH	98.4	LL=226 PL= 63 PI=163	2.7
USS Agrichem Rockland N-7 (from liter.)	CH		LL=190 PL= 36 PI=154	2.9
USS Agrichem N-4 (measured)	CH	97.9	LL=151 PL= 38 PI=113	2.86

3.1.2 Chemical Characteristics

Chemical parameters of the selected samples, as reported in the literature, are given in Table 3.2. The results of X-ray diffraction (XRD) tests run by the Florida Institute of Phosphate Research for this research effort are given in Table 3.3. The findings show that the clays are primarily fluorapatite and silica, with small amounts of calcium carbonate, dolomite, and mixed silicates. Presumably, the silicate portion is calcium montmorillonite, the dominant clay mineral in phosphatic clays. These results are consistent with the database of mineralogical information on phosphatic clay (FIPR, 1982). XRD tests were also run on clays amended with lime, lime and gypsum, and cement, which had been cured for over 180 days. Interestingly, lime residual could not be identified in the lime amended clays, nor could gypsum residual be identified in samples originally mixed with lime and gypsum. Levels of flourapatite and silica were reduced in nearly every case after amendment and curing. This would indicate that the lime has reacted with the silica in the clay in the presence of water to form other compounds, possibly a calcium silicate compound. Phosphatic waste clays are natural pozzolans because they exhibit cementitious properties when mixed with lime and water.

Table 3.2

CHEMICAL PARAMETERS (FROM LITERATURE SEARCH)

Sample	Category	Value
Mobil Nichols	pH	6.82
	P_2O_5	9.7 %
	CONDUCTIVITY	500
IMC Haynsworth D		
USS Agrichem Rockland N-7	pH	7.1
	P_2O_5	12.2%
	U_3O_8	149 ppm
	CONDUCTIVITY	610
USS Agrichem S. Rockland Mine	Total Clay	53 % *
	Palygorskite	35 % *
	Smectite	10 % *
	Illite	0 % *
	Kaolinite	2 % *
	Apatite	26 % *
	Quartz, Feldspar, and Dolomite	11 % *
	Wavelite	0 % *

* Relative peak amplitude (100R) of prospect core samples

Table 3.3

X-RAY DIFFRACTION ANALYSIS

APPROXIMATE PERCENTAGES

Sample	Fluorapatite	Silica	$CaCo_3$	Dolomite
Clay A	67	33		
Clay B	87	13		++
Clay C	56	44	(+ Mixed Silicates)	
A-2-10-L	60	30	++	
A-2-10-LG	60	30	(+ Mixed Silicates)	
A-2-20-L	37	50		++
A-2-15-C	54	28	++	(+Wilkeit)
A-8-10-L	58	42	++	
B-2-10-L	85	10	++	
C-2-10-L	45	36	++	(+Mixed Silicates)

STANDARDS

LIME	98% LIME
GYPSUM	90% GYPSUM 10% Quartz
CEMENT	40% Ca_2SiO_4 33% $Ca_2(Al,Fe)_2O_5$ 27% Other Silicates

Source: Florida Institute of Phosphate Research (1987)

3.2 SHEAR STRENGTH

The shear strength of phosphatic clay is greatly increased when amended with various amounts of lime, lime and gypsum, and cement. The amount of strength gained depends on the initial strength of the clay, the amount of amendment, the amount of time the clay is allowed to cure, and the chemical properties of the clay itself. In general, the mixes with 30 percent cement obtained the highest ultimate strengths, followed by the lime mixes and then lime/gypsum mixes. A complete listing ofthe strength test results presented on a computer printout is on file at the Florida Institute of Phosphate Research.

3.2.1 Effect of Initial Moisture Content

Initial moisture content of the clay is a key factor for the practical implementation of lime columns with phosphatic clay. In other parts of the world, experience has shown that a minimum strength of clay (corresponding primarily to the initial moisture content of the clays) exists below which the manufacture of lime columns is not economically practical. Historically, that strength value has been found to be approximately 40 psf, at or near the liquid limit of the soil. Clays with a strength of 40 psf or less would require more lime/amendment to increase the strength to a sufficient level for commercial or residential use, which would in turn drive the cost higher.

Although a detailed economic analysis was beyond the scope of this project, research performed under this contract appears to support the above observations. Samples of phosphatic clay with a strength of about 42 psf had an initial moisture content of 130 to 210 percent (32-43% solids content). In order to reach the 4000 to 8000 psf strength range required for construction of 1- to 2-story buildings, 15 to 20 percent lime had to be added to the clay. Samples with a high initial moisture content would require more lime to reach design column strengths, and may therefore be economically unattractive due to the cost of additional lime.

3.2.2 Effect of Lime Content

Adding lime to the clays has the immediate effects of reducing both the plasticity and water content, and increasing the strength. Much of the immediate increase in strength is probably due to the drying out of the clays as hydration occurs with the lime. Additionally, the strength increase is time dependent, which is thought to be caused by continued hydration and the pozzolanic reaction discussed above.

Figure 3.1 illustrates the time dependence of strength increase on sample mix B-2 (Clay B with 42 psf initial strength) for various lime contents. The pattern of strength increase versus time for 6 and 10 percent lime indicates that the strength continues to increase only moderately after about 90 days. The sharp increase in strength after 90 days for some mixes is considered spurious above about 20,000 psf, the upper level of accuracy for the fall cone.

The pattern of increasing strength with increased lime content is typical of other mixes. As lime content is increased, both the initial strength gain and the cured strengths increase (Figures 3.2, 3.3, and 3.4). The benefit of increasing the lime content appears to peak between 15 and 20 percent lime.

Strength increase with lime mixtures were sometimes remarkable. Even with clays having the weakest initial strength (42 psf), samples increased in strength 30 times the original strength by 180 days with only 6 percent lime added (e.g., B-2-6L). In all, 80 samples tested by the fall cone method reached strengths above 20,000 psf. Clay A from Mobil gained the highest strengths when amended with lime, followed by Clay B from Brewster and then Clay C from USS Agrichem (e.g. Figure 3.5). This may indicate a

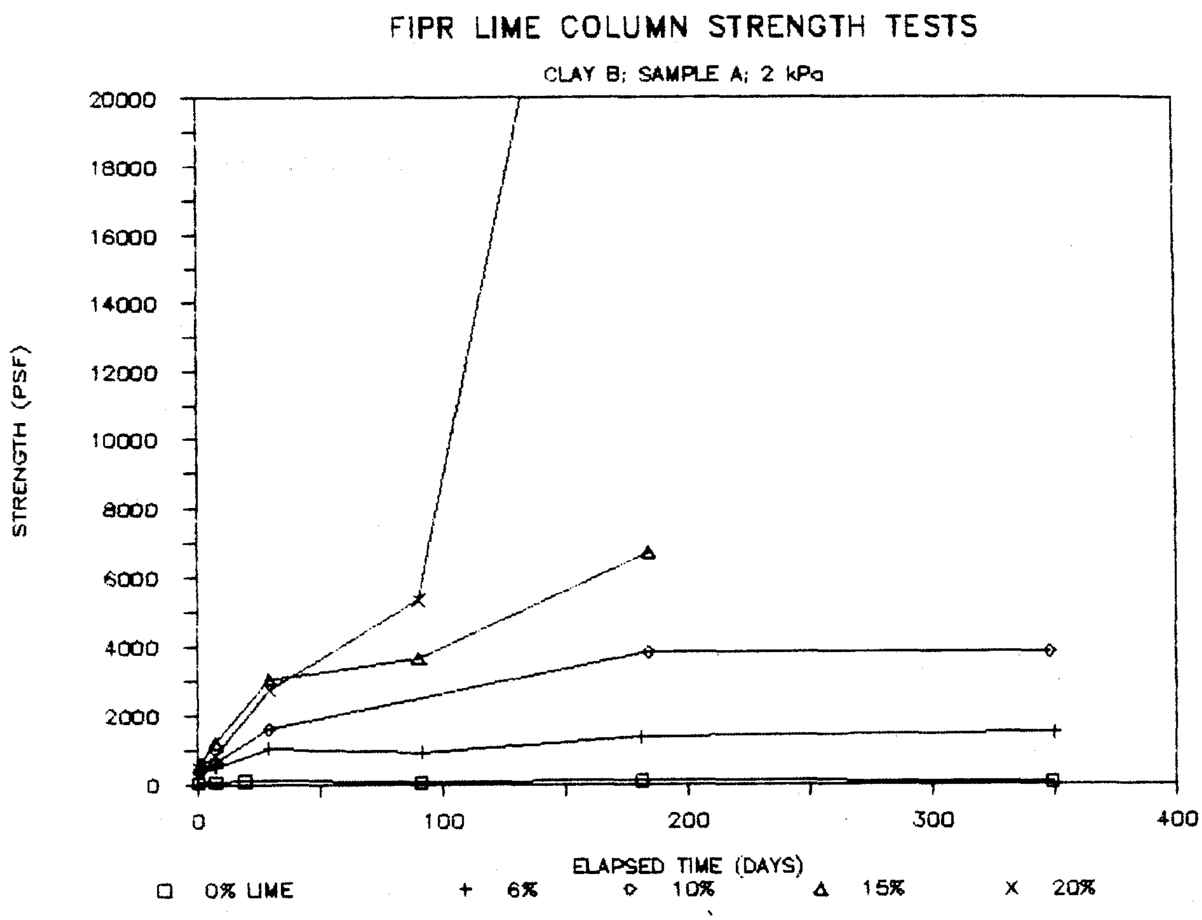

Figure 3.1 Effect of curing time and lime content on clay B at 2kPa (40 psf) initial strength.

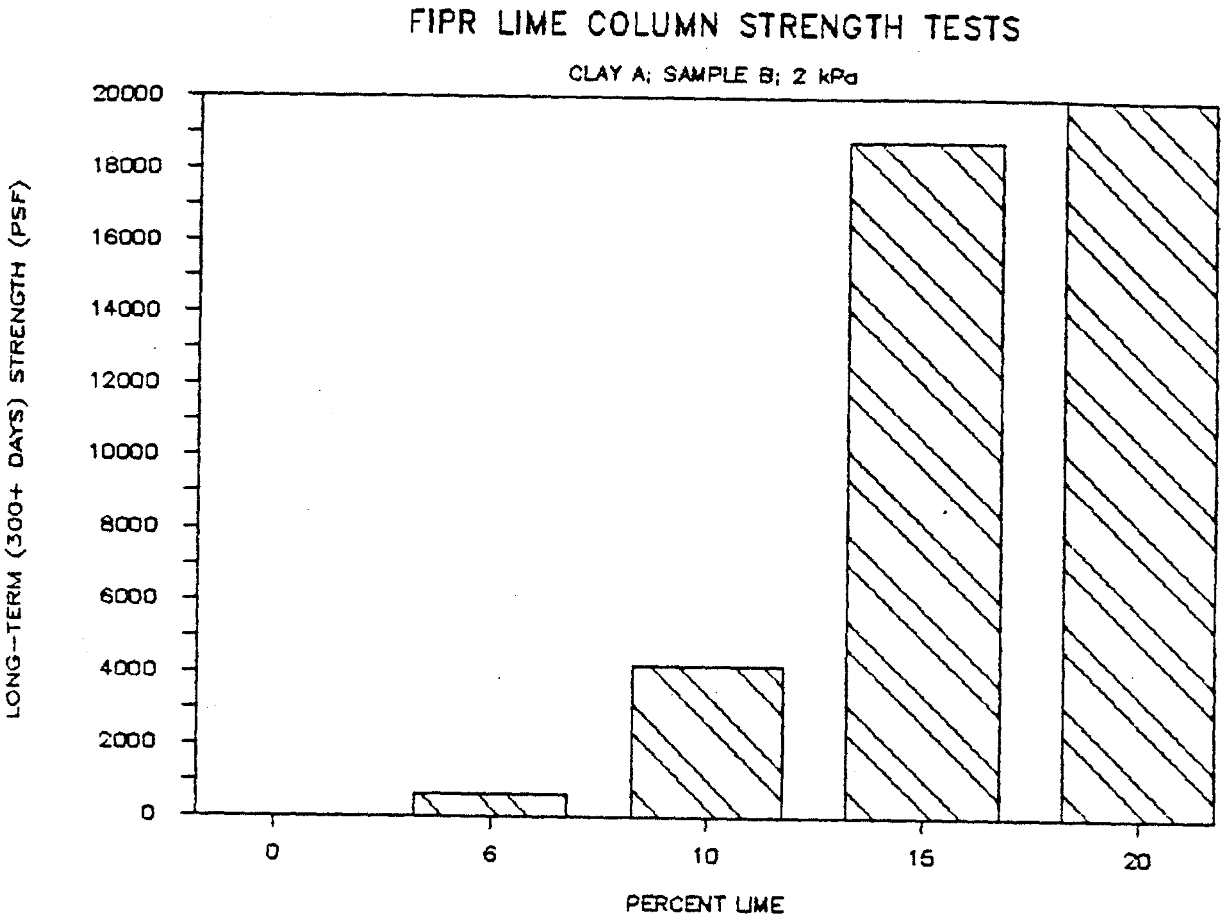

Figure 3.2 Effect of lime content at 300+ days elapsed curing time for clay A-2.

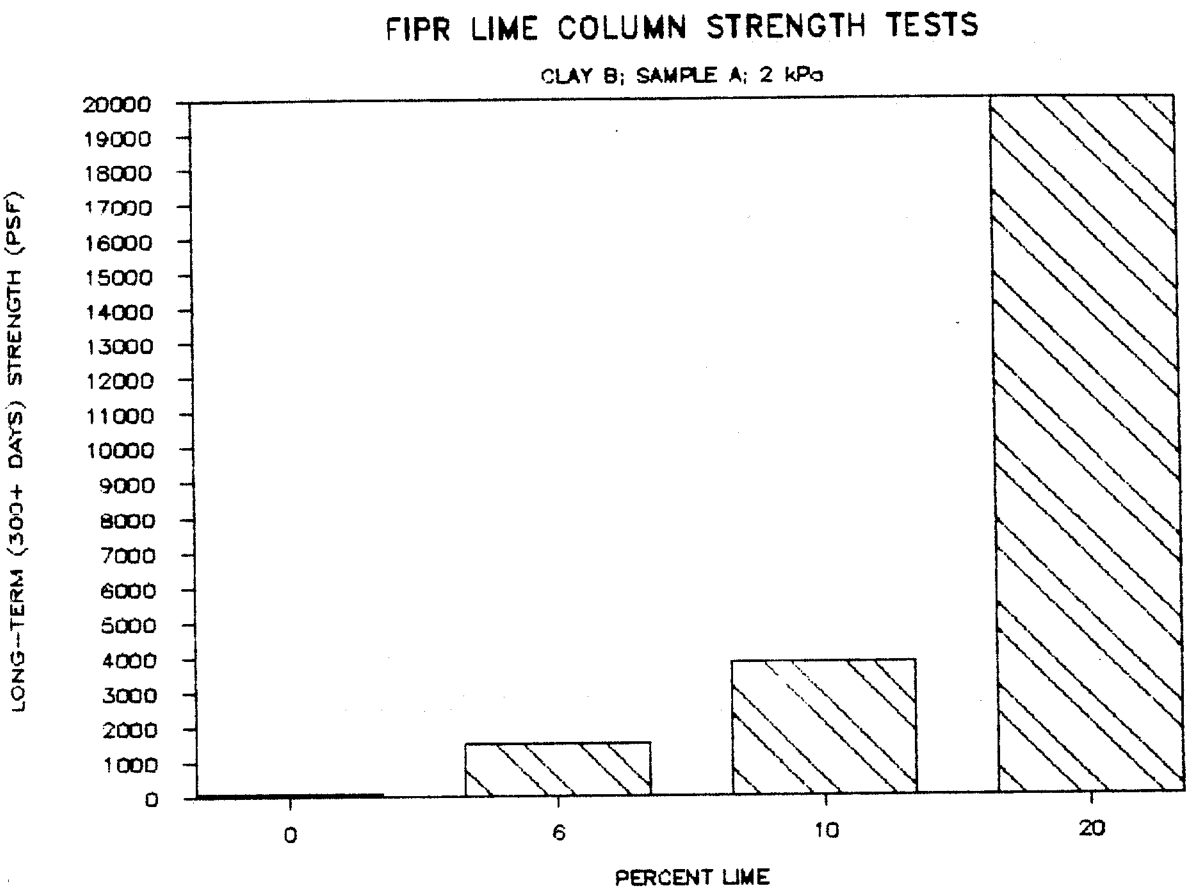

Figure 3.3 Effect of lime content at 300+ days elapsed curing time for clay B-2.

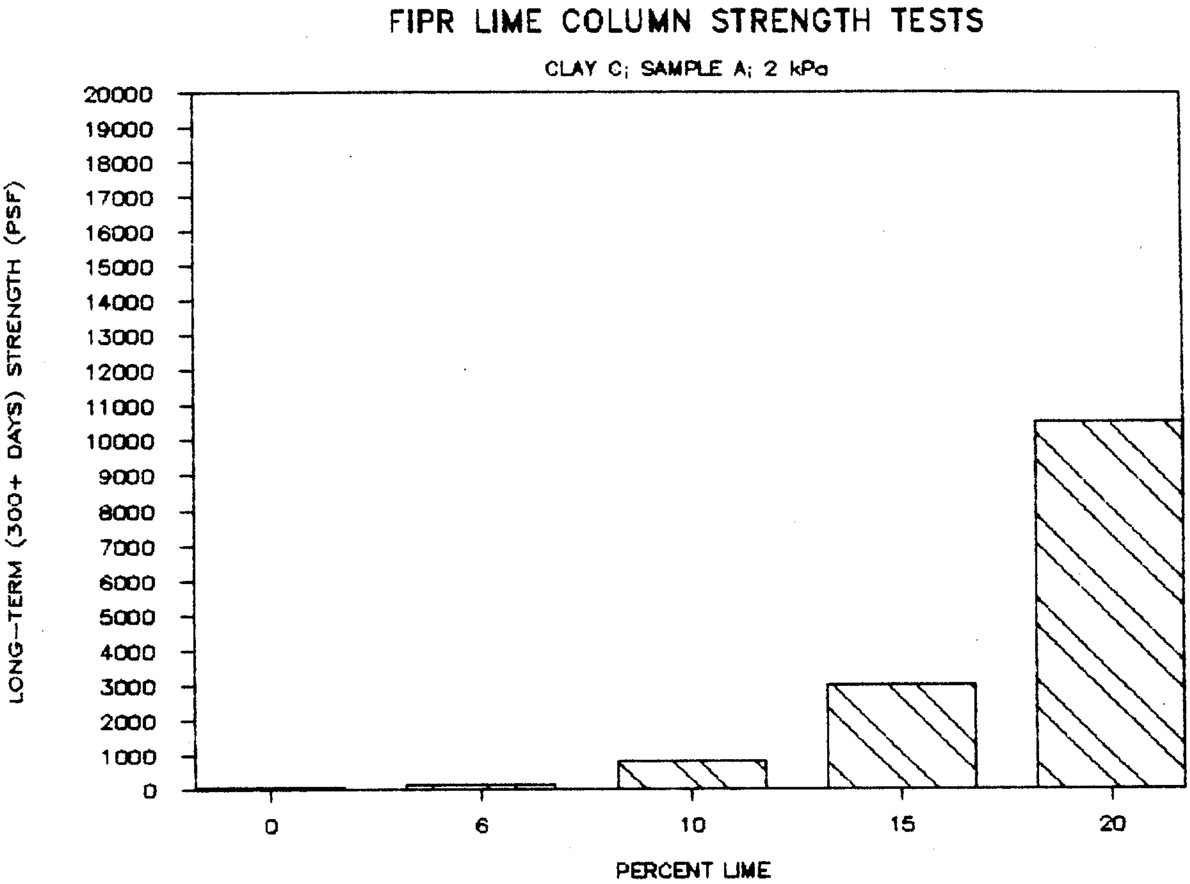

Figure 3.4 Effect of lime content at 300+ days elapsed curing time for clay C-2.

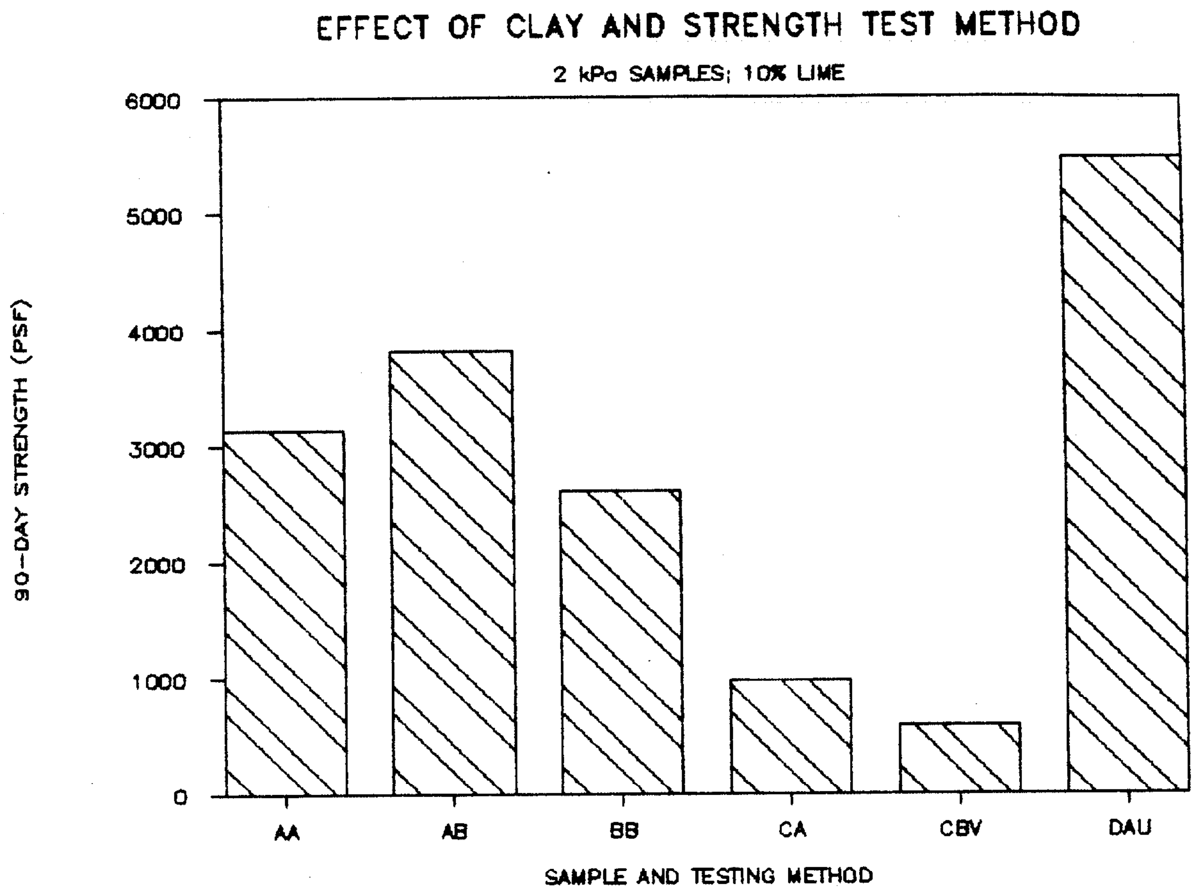

Figure 3.5 Comparison of 90-day strengths for different clays and testing methods.

relationship between the plasticity and strength gain with lime, since Clays A, B, and C were selected in order of decreasing PI.

3.2.3 Effect of Lime and Gypsum Mix

Lime and gypsum mixtures (2/3 lime to 1/3 gypsum) were added to clay mixtures at 10 and 20 percent by weight. Mixes with 20 percent lime/gypsum mixtures produced ultimate strengths 2 to 3 times that of the 10 percent mix. A comparison of the strengths of lime/gypsum/clay mixes to lime/clay mixes gave two notable observations. Lime and gypsum mixes generally exhibit a) higher early strengths and b) lower ultimate strengths than lime only mixes (Figures 3.6 and 3.7).

3.2.4 Effect of Cement

Mixes with 15 percent cement often had lower strengths than either 10 percent lime and gypsum or 15 percent lime. However, mixes with 30 percent cement were considerably stronger than either lime only or lime/gypsum mixes (Figure 3.8). Even clays with a low initial strength of 42 psf reached over 4000 psf after about 1 year when mixed with 15 percent cement (Figure 3.9).

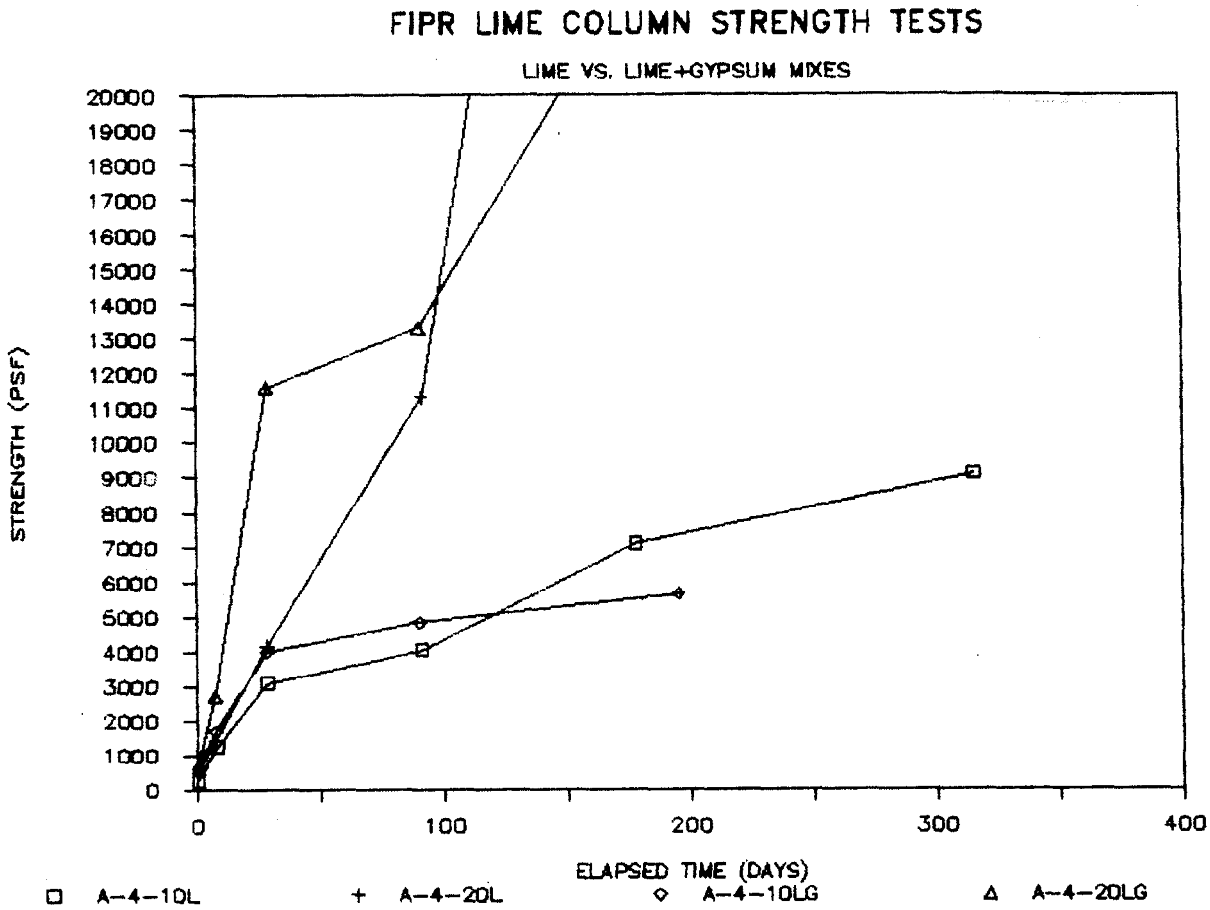

Figure 3.6 Comparison of strength gain characteristics for lime and lime/gypsum amendments (clay A).

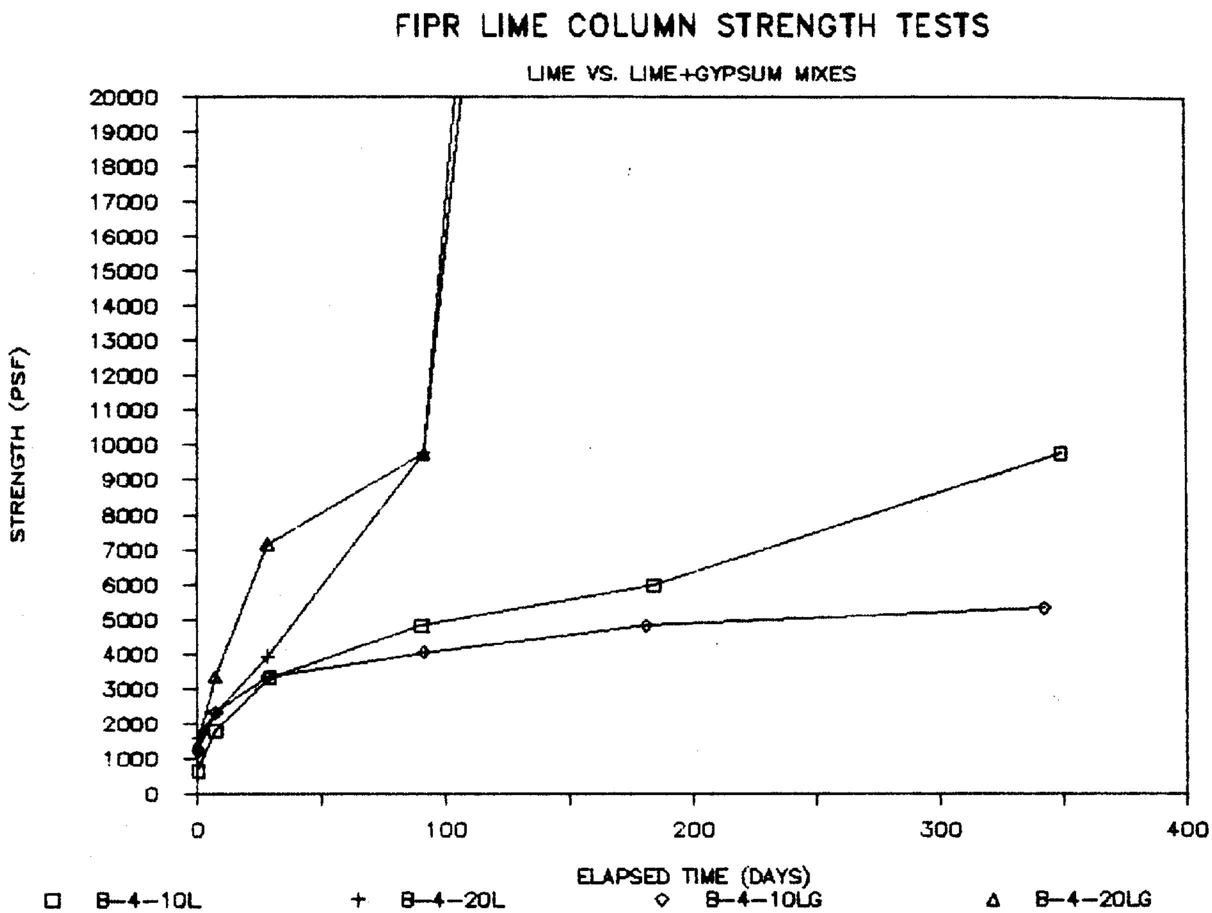

Figure 3.7 Comparison of strength gain characteristics for lime and lime/gypsum amendments (clay B).

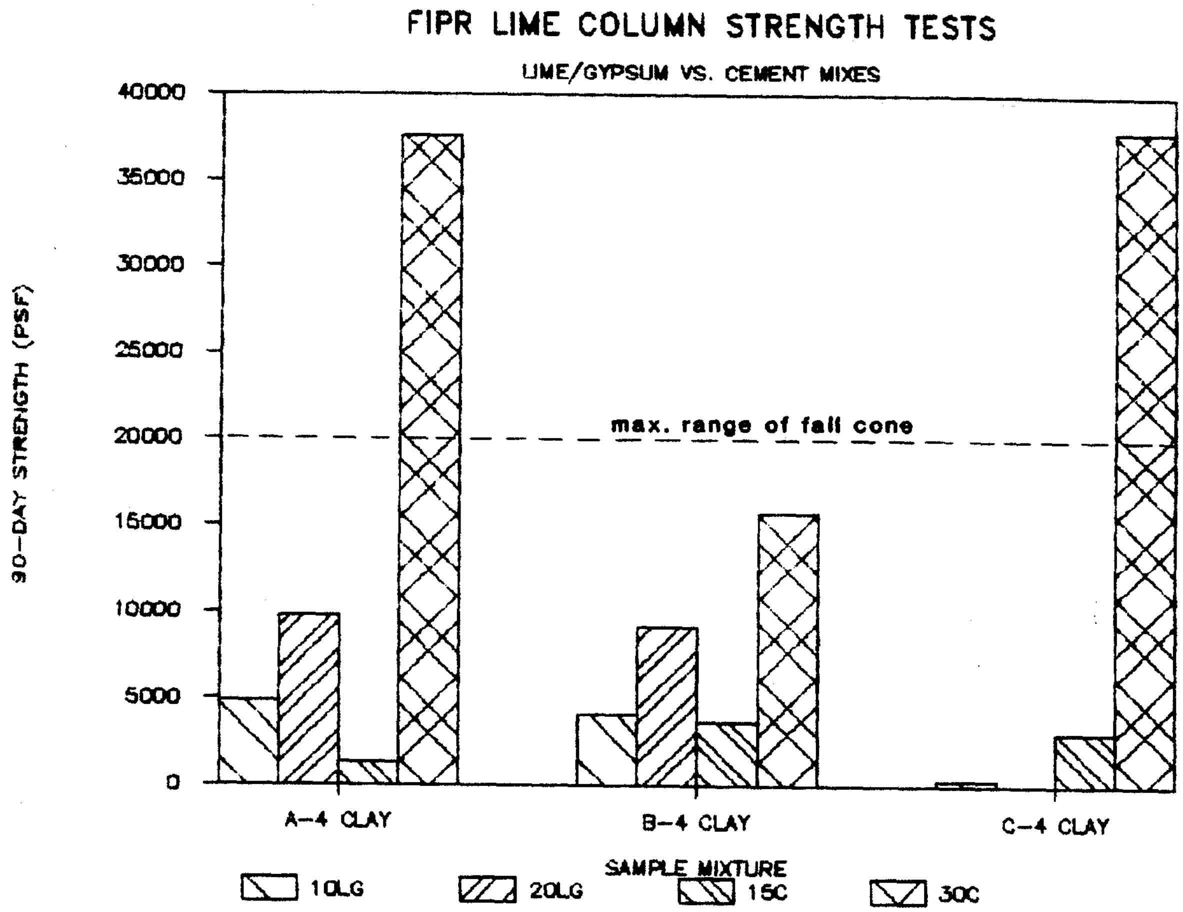

Figure 3.8 Comparison of 90-day strengths for lime/gypsum and cement amendments.

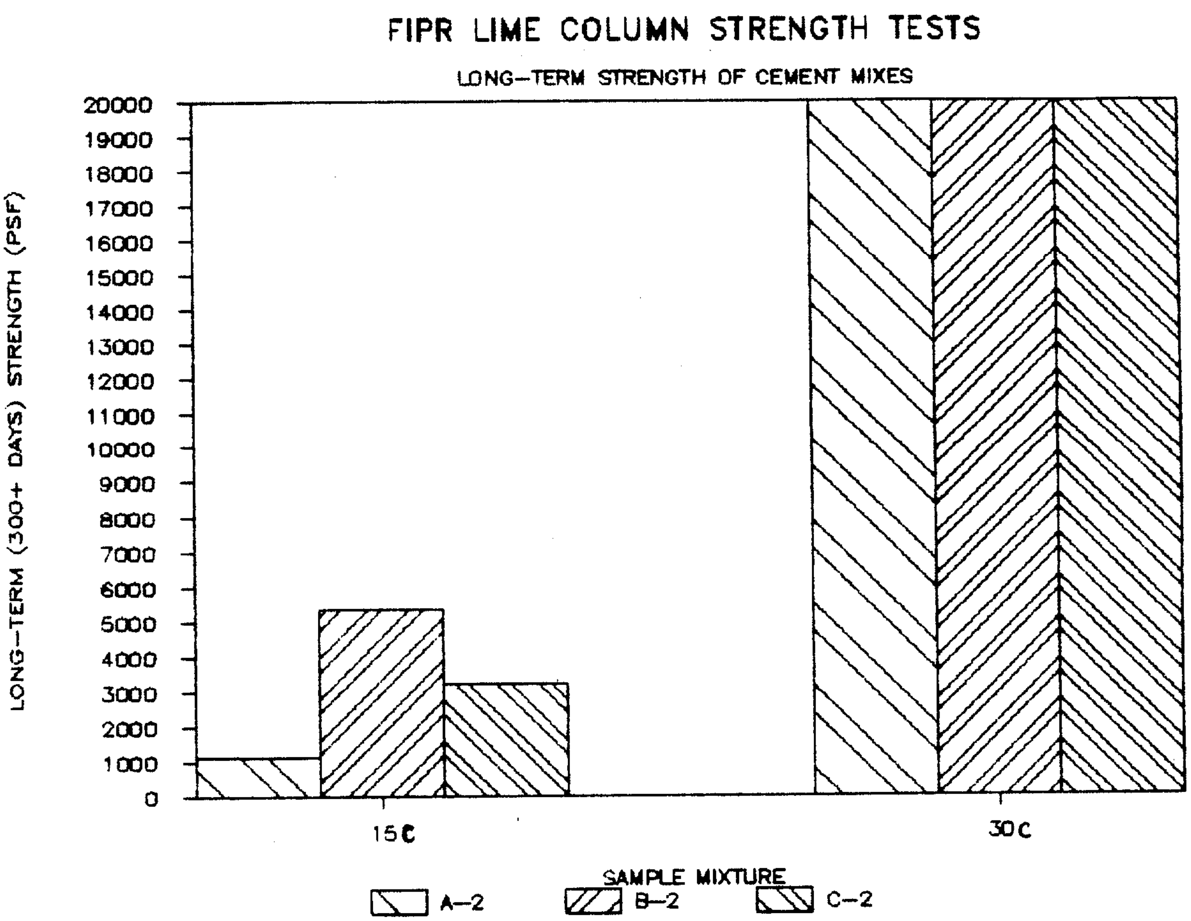

Figure 3.9 Long-term strength of clay/cement mixes.

Many cement mixes exhibited strengths beyond the readability of the fall cone apparatus and were tested by the unconfined compressive strength method. Of 34 samples tested at over 300 days, 23 had a strength greater than 20,000 psf. In the presence of sand (clays D and E), strengths increased further. Sandy/clay mixes with cement were essentially concrete grout mixtures.

3.2.5 Long-term Strength Measurements

Long-term strength teats were run on all mixes at the same time, rather than at the 360-day interval. This procedural change increased the efficiency of the testing program and allowed all of the samples to be tested before the deadline of the research effort. Nearly all mixes were cured for longer 300 days, while some were cured for more than 400 days.

Strengths continued to increase after the 180-day readings. Of the mixes with strengths within the reliable limits of the fall cone (maximum 20,000 psf), an average increase in strength of 10 percent was measured from the 180-day strengths to the long-term (greater than 300 days) strengths.

3.2.6 Comparison of Various Methods of Strength Measurement

The majority of strength measurements were made with the fall cone apparatus. This device has been used successfully in Europe and can measure strengths over a wide range of values, due to several different size cones. The fall cone can measure strengths as low as 1.3 psf and as high as 20,000 psf. Although measurements of strength above 20,000 psf were made on the stronger mixes, the accuracy of the strength reading is greatly reduced as the penetration of the cone is also reduced. Fall cone strengths greater than 20,000 psf are certainly suspect, and the "jump" in strength noted on many of the graphs after 90 or 180 days is thought to be caused by inaccuracies in the measurement and not due to a sudden strength gain in the material.

Vane shear strength measurements were made with a 19 mm Pilcon portable vane shear device. The vane is manufactured in England and has a direct readout of triaxial shear strength in units of kiloPascals. A correction factor of 1.346 was made to the readings to convert them to equivalent vane shear strength readings. The vane shear method was only used on relatively weak samples, as the maximum strength of the device is 3300 psf.

Vane strengths were on the order of 78% ± 8% of the fall cone strengths. Remolding the samples further reduced the vane strength values to only 23% ± 9% of the maximum vane strengths. Remolding of the lime columns mixtures, therefore, lowers the strength considerably, presumably due to the loss of cemented bonds within the soil structure.

Unconfined compression tests were run on sand/clay mixes only (Clays D and E) which proved to be above the range of the fall cone device. These strength test results were characterized by high scatter. Additionally, strengths were on the order of 15 to 25 percent of the fall cone strengths. This is primarily because samples tended to crumble at the ends and break at weak planes of compaction. Consequently, strengths were more a function of sample preparation than percentage of admixture. However, results did indicate an increase in strength with time.

3.2.7 Further Discussion of Strength Results

Strength increase of the soft clay must be substantial for lime columns to be practical. Results of this study indicate dramatic increase in strength of phosphatic clay admixtures, with more than a third of the mixes attaining a final strength greater than 20,000 psf. Final shear strengths of 4000 to 8000 psf correspond to a column capacity of at least 6,500 to 13,000 lbs. for a 1.6 foot diameter column. This assumes, based on experience from lime columns manufactured in Europe, that the column strength is about 2/3 of the laboratory cone strength.

A comparison of these strength results with those done in an in-house study at FIPR are similar (Barwood, 1986). Initial solids contents of clays in that study ranged from 5 percent to 30 percent, as compared to 33 to 47 percent solids for this study. The best comparison of results between the two studies can be made by reviewing the data for 10 percent lime added (Figure 3.10). No strength gain was noted on any clay with an initial solids content of 10 percent or less. Clays at 20 per cent solids achieved strengths beyond 70 psf, the maximum reading for the penetration device used in the FIPR study.

3.3 PLASTICITY

All admixtures caused a marked reduction of the plasticity, as measured by Atterberg limits. The change in plasticity with time was checked during the first month of curing. Results of Atterberg Limits tests are summarized in Table 3.4. The initial reduction in the plasticity index is caused primarily by a significant increase in the plastic limit. Test results also indicate that plasticity index

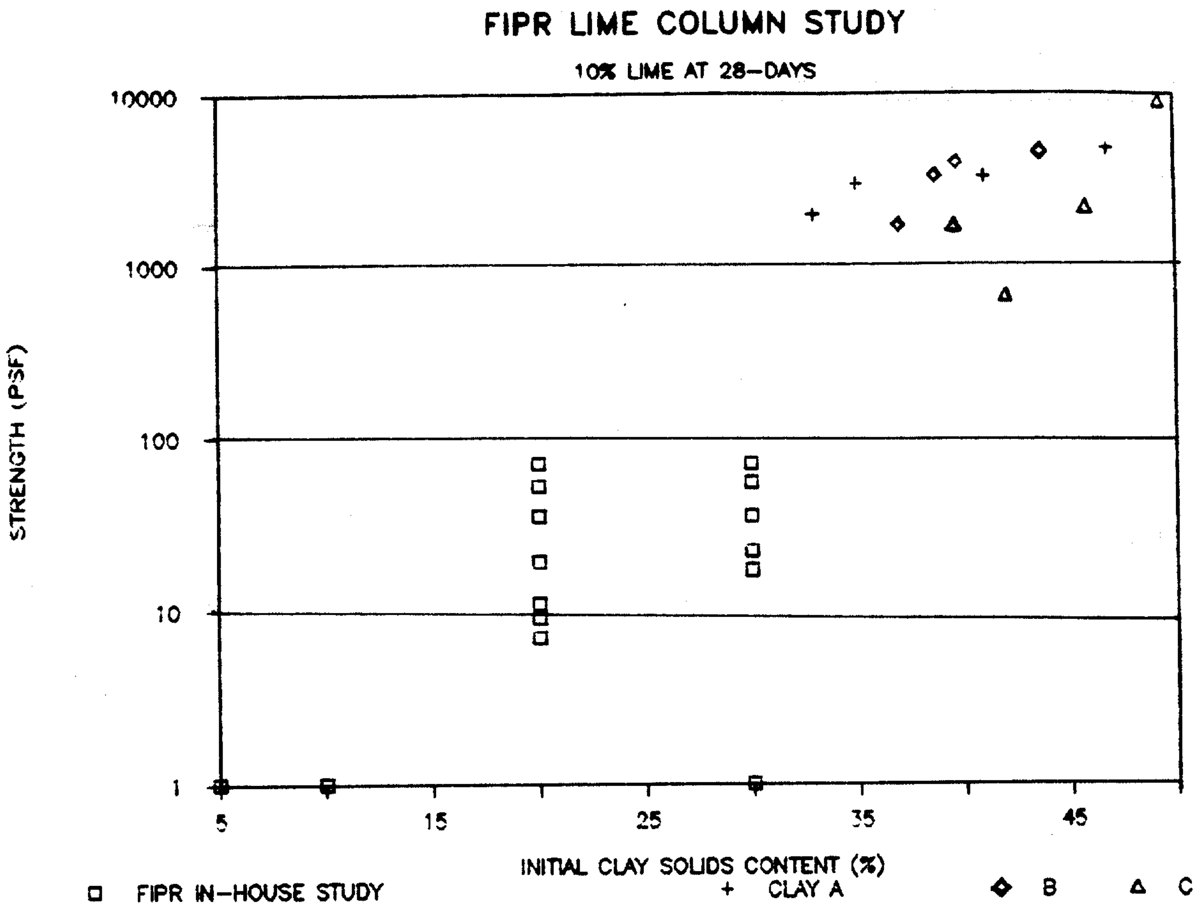

Figure 3.10 Comparison of lime column study and FIPR in-house study of lime amendments.

Table 3.4
ATTERBERG LIMIT RESULTS

CLAY	INIT STR (kPa)	MIX (%)	CURE DAYS	ATTERBERG LIMITS LL	PL	PI
A		0L	0	184	33	151
A	4	2L	0	286 *	99	187
A	4	2L	7	266 *	82	184
A	4	6L	1	153	100	53
A	4	6L	9	178	108	70
A	4	6L	29	181	108	73
A	4	10L	1	179	101	78
A	4	10L	8	176	103	73
A	4	10L	29	183	96	87
A	4	15L	1	179	99	80
A	4	15L	8	174	103	71
A	4	15L	29	168	107	61
A	4	20L	1	171	90	81
A	4	20L	7	165	101	64
A	4	20L	29	159	104	81
A	4	10LG	7	190	133	64
A	4	10LG	29	186	106	55
A	4	20LG	8	164	111	57
A	4	20LG	29	163	115	48
A	4	15C	9	197	88	109
A	4	30C	1		89.2	
A	4	30C	8	166	124	42
A	4	30C	29	159	114	45
B	4	0L	0	226	63	163
B	4	0L	1	203 *	48	155
B	4	0L	7	195 *	90	105
B	4	6L	1	217 *	122	95
B	4	6L	7	210 *	100	110
B	4	10L	1	216 *	114	102
B	4	15L	1	234 *	114	120
B	4	20L	1	203 *	97	106
B	4	20L	7	209	99	110
B	4	20L	29	142	103	39
B	4	10LG	0	231 *	64	167
B	4	10LG	8	220	116	104
B	4	10LG	28	197	97	100
B	4	20LG	0	206 *	115	91
B	4	20LG	7	212	137	75
B	4	20LG	29	173	106	67
B	4	15C	0	223 *	89	134
B	4	15C	8	237	143	94
B	4	15C	28	194	89	105
B	4	30C	0	188 *	87	101
B	4	30C	8	195	121	74
B	4	30C	28	163	103	60

Table 3.4 (Continued)

CLAY	INIT STR (kPa)	MIX (%)	CURE DAYS	ATTERBERG LIMITS LL		PL	PI
C	4	0L	0	151		38	113
C	4	0L	2	188	*	93	95
C	4	0L	8	189	*	30	150
C	4	6L	1	154	*	90	64
C	4	6L	29	159	*	74	85
C	4	10L	1	155	*	83	72
C	4	10L	7	144	*	79	65
C	4	10L	31	140		96	44
C	4	15L	2	173	*	91	82
C	4	15L	7	161	*	104	57
C	4	15L	28	161	*	90	71
C	4	20L	1	160	*	86	74
C	4	20L	29	137	*	89	48
C	4	10LG	1	155	*	86	69
C	4	20LG	1	203	*	114	89
C	4	20LG	7	173	*	110	63
C	4	20LG	31	171		129	42
C	4	15C	1	216	*	101	115
C	4	15C	7	202	*	87	115
C	4	15C	31	195		104	91
C	4	30C	7	137	*	99	38
C	4	30C	28	135	*	84	51

* Liquid limit value may be high due to worn groove tool

continues to decrease with time, although the long-term change is small compared to the initial reduction in the plasticity when the clay and lime are mixed.

3.4 pH AND MOISTURE CONTENT

The pH of clay admixtures was immediately raised from a range of 7.0 to7.7 for untreated clay to a range of 11.8 to 12.8. Mixes with 15 percent cement had the lowest pH while mixes with 20 percent lime had the highest. In addition, the pH decreased just slightly with time as curing occurred (Figures 3.11 and 3.12).

Tests run by Arman (1986) on phosphatic clay used in this study (Clay B) were run as per Eades and Grim (1960). The optimum lime content according to this method was 6 percent by weight, producing a pH of 12.4. While the pH is in agreement with our study, 6 percent lime does not correspond to the optimum strength for lime and phosphatic clay mixtures. This is primarily because the unhydrated lime in excess of 6 percent is incorporated into the hydration of water in the waste clay, which is typically at a much higher moisture content than other soils normally associated with the Eades and Grim procedure. Therefore, due to the high initial water content of the clays, the pH alone does not appear to be a valid indicator of the optimum lime content.

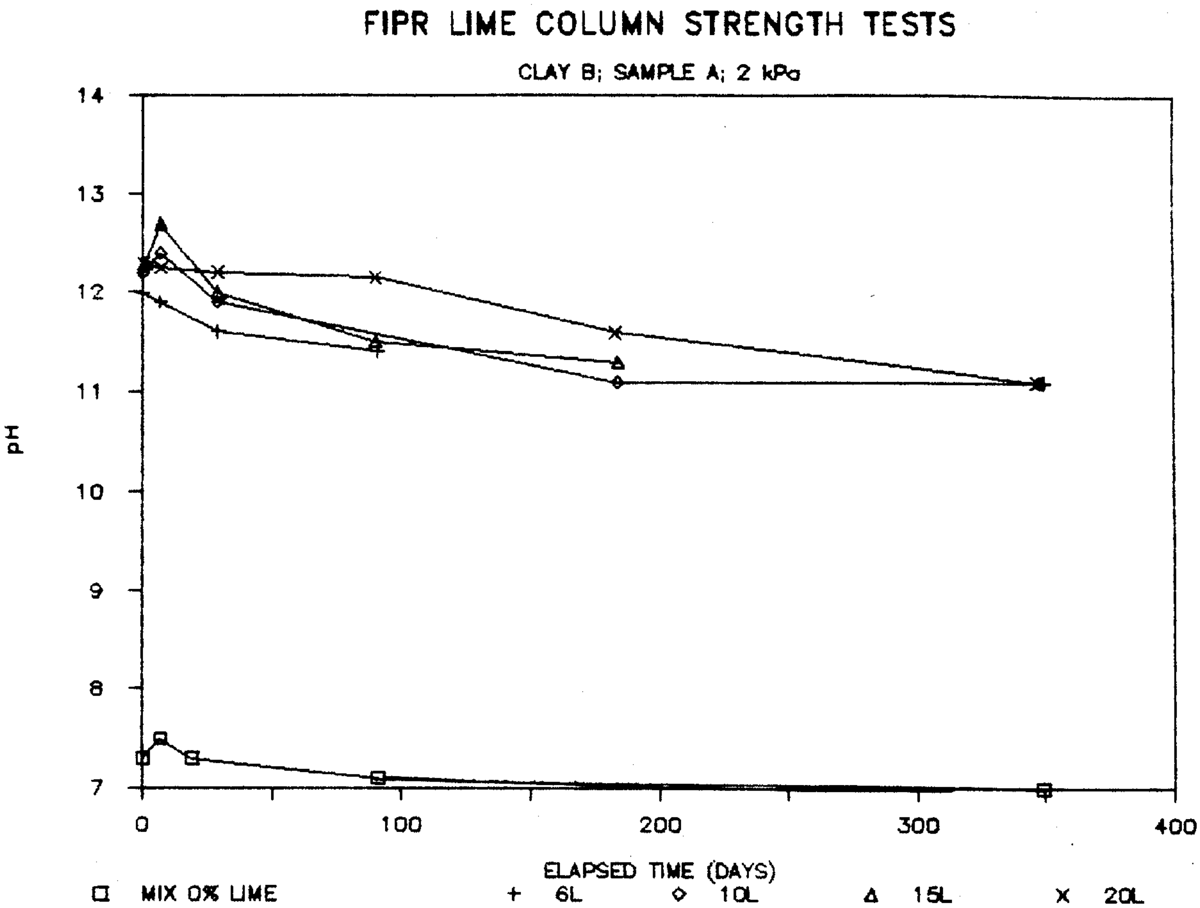

Figure 3.11 Effect of lime content on the pH of a sample at 2kPa initial strength.

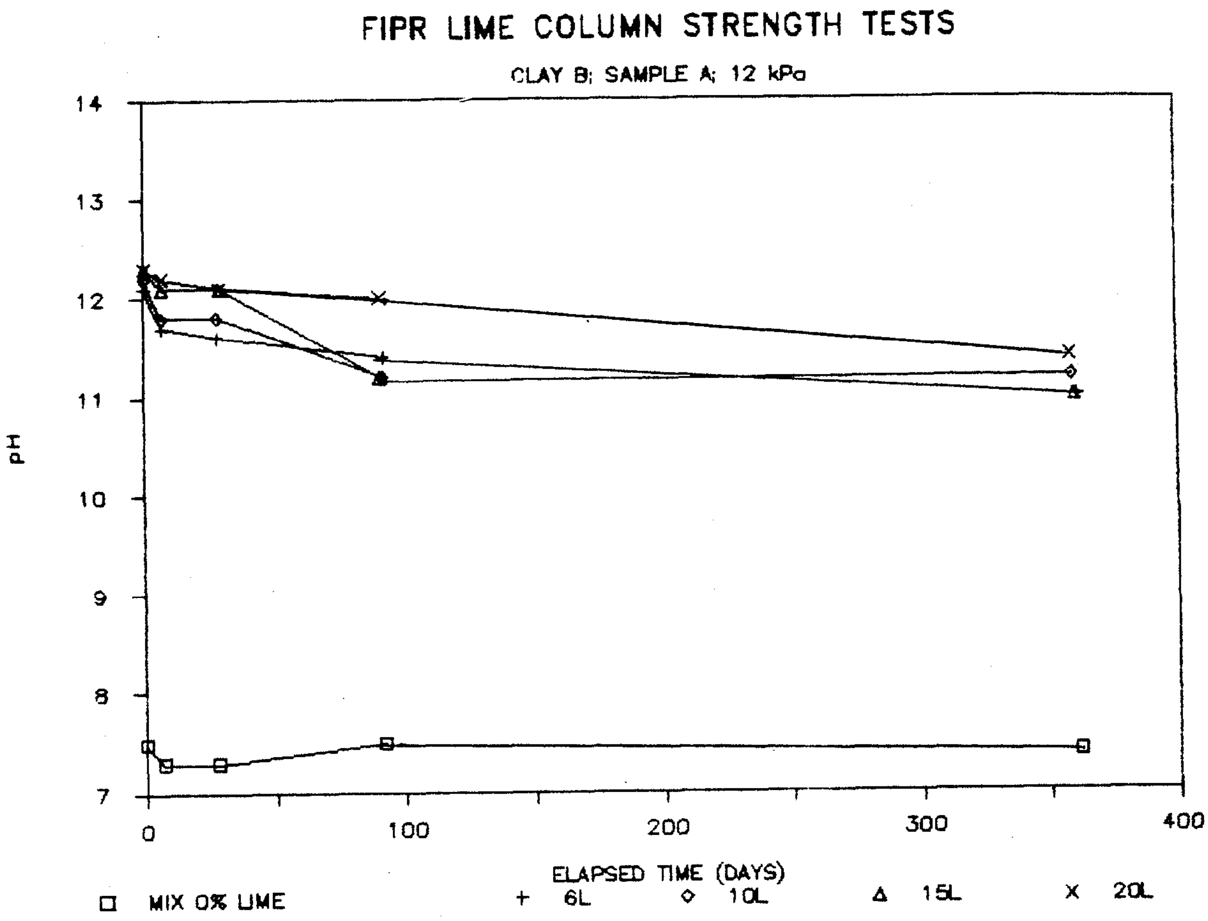

Figure 3.12 Effect of lime content on the pH of samples at 12 kPa initial strength.

It may, however, indicate a minimum amount of lime required to effectively increase the strength of phosphatic clays.

The moisture content of the clay is decreased when lime, cement or lime/gypsum mix are incorporated into the clay. By adding just 6 percent lime, the moisture content is decreased by 10 to 13 percent immediately. Lime and lime/gypsum mixes appear to pull nearly the same amount of water out of the clay, while cement is about 5 to 10 percent less effective in lowering the moisture content. The moisture content did not appear to vary significantly with time, probably because samples were completely submerged during the curing process.

3.5 COMPRESSIBILITY

Definition of Terms

A description of the terms and parameters used to describe consolidation phenomenon are provided prior to presentation of results. Figure 3.13 illustrates a typical consolidation curve and the parameters.

Compressibility of a clay is usually expressed in terms of the compression index (C_c), the recompression index (C_r), and the preconsolidation pressure (P_c). When a series of increasing loads is applied to a clay soil, the amount of

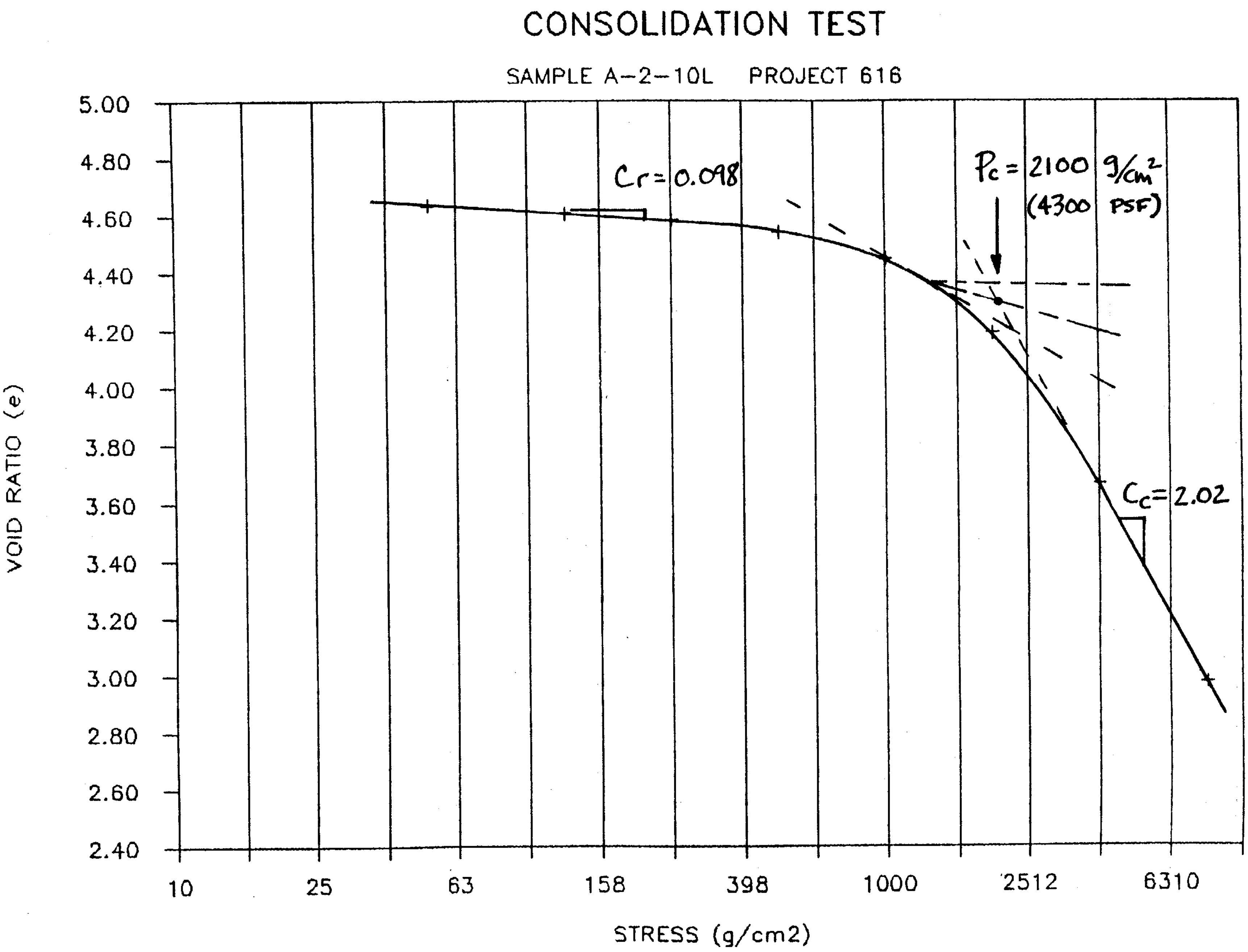

Figure 3.13 Typical consolidation (e-log stress) curve for amended clays.

compression occurring up to the magnitude of the maximum past pressure or preconsolidation pressure is relatively small. Stresses exceeding P_c enter the "virgin" portion of a stress-strain curve, and substantially greater compression occurs. It may be expressed by the compression index C_c, the slope of the virgin compression or void ratio vs. log time curve expressed by:

$$C_c = \frac{-\Delta e}{\log(\bar{\sigma}_f/\bar{\sigma}_i)}$$

where Δe = change in the void ratio (e); a measure of the volume change in the soil
$\bar{\sigma}_f$ = final effective stress, and;
$\bar{\sigma}_i$ = initial effective stress.

The recompression index is calculated the same way as the compression index, over the flatter portion of the curve. P_c, C_c, and C_r are illustrated graphically in Figure 3.13 for mix A-2-10L.

For this study, samples of clay from the three selected mines were tested for compressibility using an oedometer, a one-dimensional consolidation apparatus. Tests were completed on Clays A and C at approximately 28 and 180 elapsed days of curing. Results of all tests are summarized in Table 3.5.

Table 3.5

SUMMARY OF CONSOLIDATION RESULTS

Mix	Preconsolidation Pressure P_c (psf)	Recompression Index C_r	Compression Index C_c	C_r/C_c*
Clay A	690		1.45*	
A-2-15C	1970	0.037	1.58	1/39
A-2-10L	4725	0.098	2.02	1/15
A-2-10L-LT	7110	0.125	2.18	1/12
A-2-20L	6480	0.059	1.42	1/25
A-2-20L-LT	11100	0.082	0.37	1/18
A-8-10L	4030	0.024	1.40	1/60
A-8-10L-LT	8450	0.117	1.51	1/12
Clay C	490		1.24*	
C-2-10L	3860	0.064	1.82	1/19
C-2-10L-LT	4290	0.093	2.46	1/13
C-2-20L	4830	0.061	1.32	1/20
C-2-10LG	1300	0.074	1.33	1/17
C-2-15C	2400	0.028		1/44
C-2-15C-LT1	5300	0.128		1/10
C-2-15C-LT2	8800	0.100	3.15	1/12
C-8-10L	4830	0.065	1.42	1/19
C-8-20L	9750	0.021	0.74	1/59
C-8-10LG	3770	0.174	1.06	1/7
C-8-15C	10400	0.043	0.64	1/29

* C_c of untreated clay.

LT - denotes long-term tests (cured over 180 days). All other data presented above is for samples cured approximately 28 days.

Deformation and Preconsolidation

The most significant aspect of the compressibility of clay/admixtures is the presence of an "apparent preconsolidation", as illustrated in Figure 3.13. Even though amended clay samples were prepared in the laboratory and had not been preloaded, every sample tested exhibited preconsolidation. This phenomenon, which has been documented for some cemented soils and some soft rocks, reflects cementing/bonding in the clay admixtures, thereby increasing the strength and reducing the magnitude of deformations below the preconsolidation pressure.

A comparison of a clay with no lime added to the same clay with 10 percent lime added is shown in Figure 3.14. Although preconsolidation is indicated in clay-only mixes (probably due to sample handling and preparation), the preconsolidation pressureis much higher for amended clays. In practical terms, this means it takes more load on the amended sample before "virgin" compression isinduced. The result is a substantially reduced overall compression or volume change within the range of anticipated field pressures where lime columns might be used (1000-2000 psf).

Preconsolidation pressure was found to be a function of a) the type of admixture, b) the percent admixture, and c) the amount of curing time. In general, cement mixes tended to

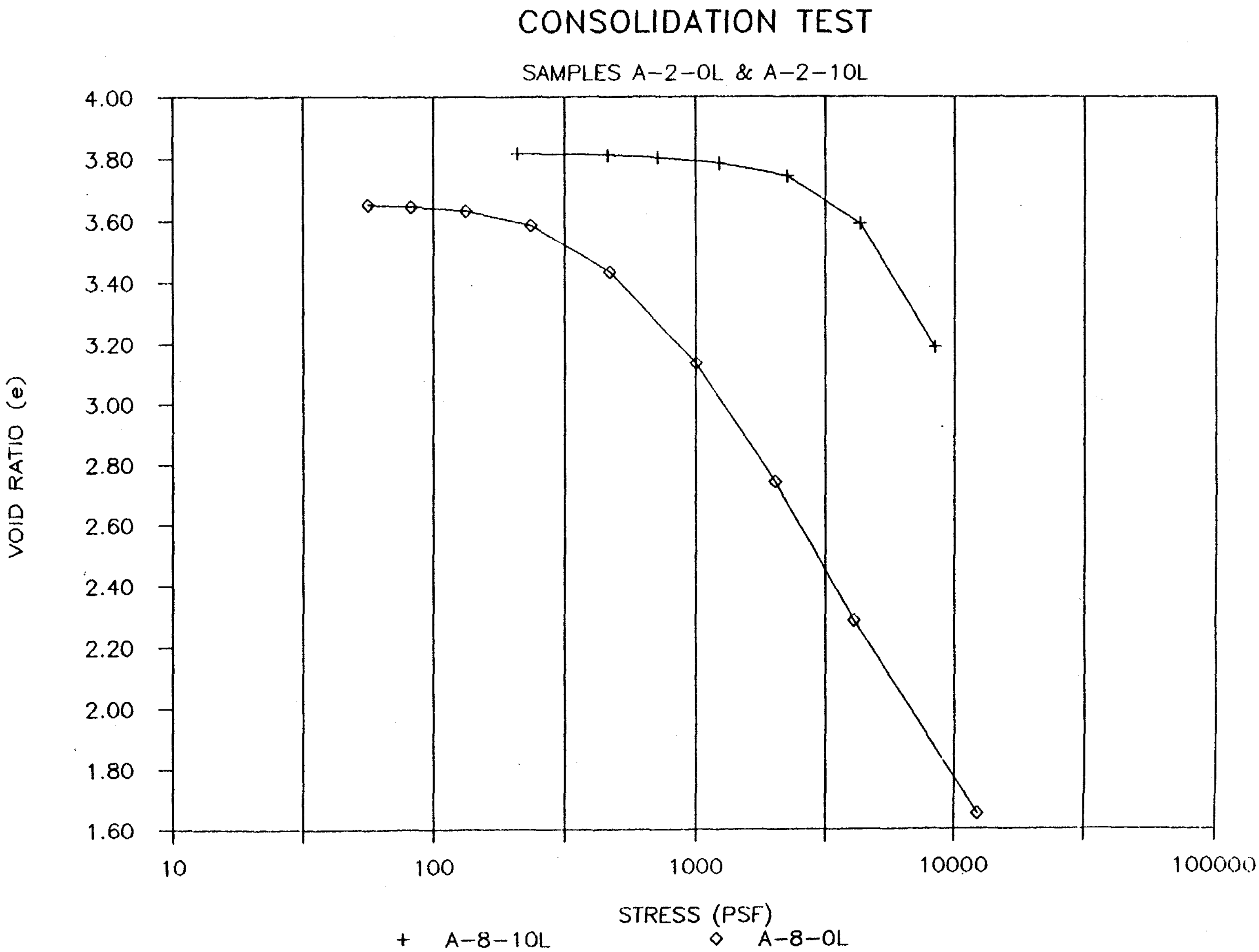

Figure 3.14 Comparison of consolidation characteristics of phosphatic clay with no lime added and 10 percent lime added

achieve the highest P_c, followed by lime mixes and then lime/gypsum mixes. In all cases, however, a higher percentage of admixture resulted in a higher P_c, as illustrated with lime in Figure 3.15.

Each of six long-term consolidation tests, when compared to the corresponding 28-day tests, exhibit an increase in the apparent preconsolidation pressure and a decrease in the overall deformation of the samples. The effect of curing on consolidation is shown in Figure 3.16. The void ratio versus log stress curves reveal an increase in strength due to continued cementation in the samples, as indicated by the increase in the apparent preconsolidation pressure, P_c, of the sample cured over 180 days.

Overall, as substantial reduction in deformation was exhibited in amended clays. In all but one test, C_r was 1/10 to 1/70 that of C_c for untreated clay (Table 3.5). Therefore, if the stresses imposed on treated clay are less than the preconsolidation pressure (e.g., in Fig. 3.13, about 2000 psf), deformations should be on the order of 1/10 to 1/70 that of untreated clay.

<u>Time Rate of Consolidation</u>

Deformations on admixtures occurred very rapidly at stresses below the preconsolidation pressure. The majority

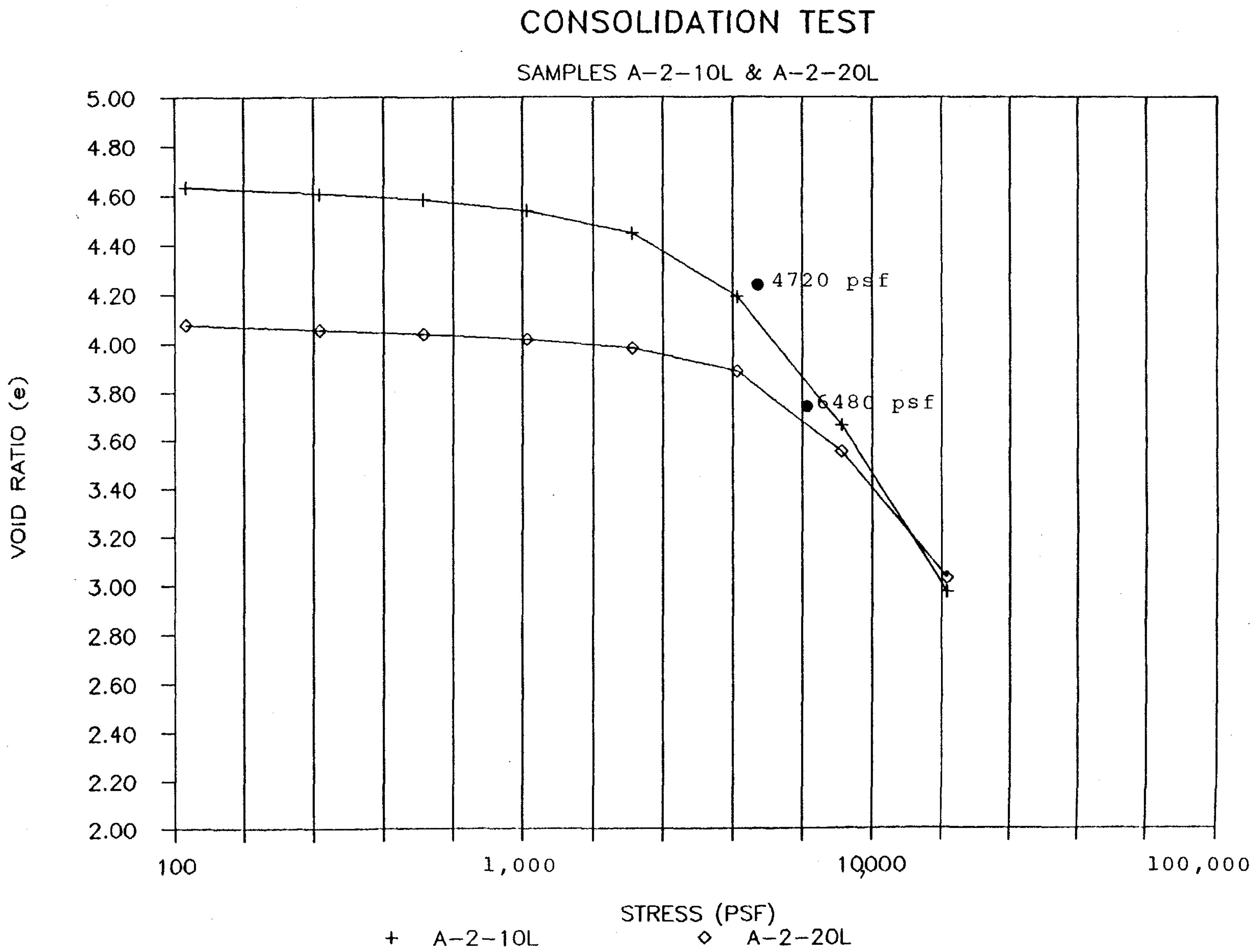

Figure 3.15 Effect of higher lime content on preconsolidation pressure

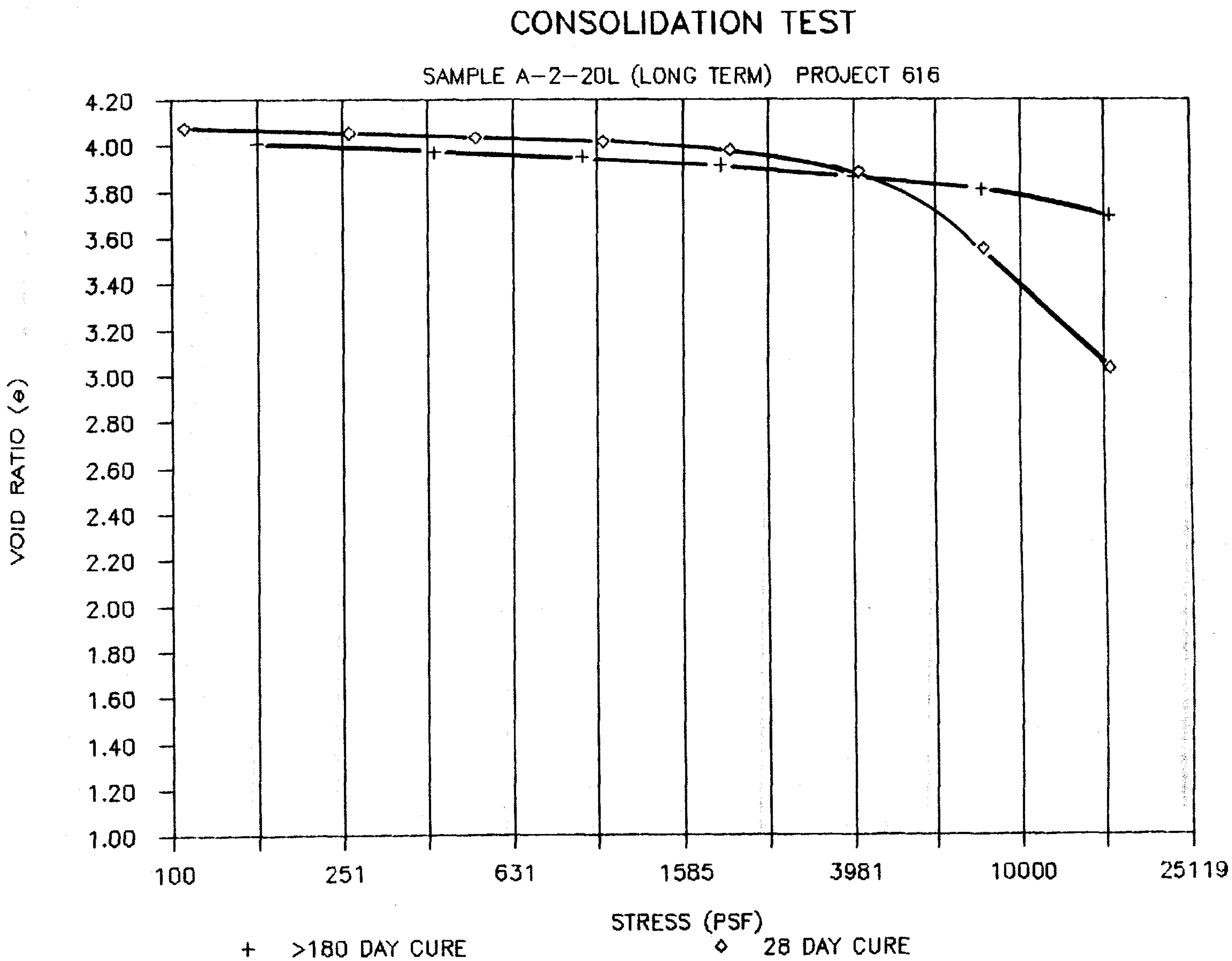

Figure 3.16 Effect of additional curing on the consolidation characteristics of sample A-2-20L.

of the deformations occurred immediately upon loading. However, admixtures exhibited time-dependent behavior typical of normal clay consolidation behavior at stresses above the preconsolidation pressure. This indicates that the deformations associated with installed lime columns would be almost immediate upon loading up to stresses equal to Pc. If stresses above Pc are imposed, the columns will act more and more like a typical clay material as cemented bonds are overcome, and the resulting deformations are more time dependent.

In summary,the results of consolidation testing indicate that lime columns with mixed phosphatic clay and unslaked lime (or cement, lime/gypsum) will have a much lower compressibility than unamended clay, and that the lime columns consolidate (deform) at a faster rate.

3.6 PERMEABILITY

A summary of the permeability test results is given in Table 3.6. The majority of the permeability tests were run with a Soil test Flexible Wall Permeameter System, by which the gradient through the sample can be controlled. Other tests were run using a falling head permeability apparatus. With the exception of four long-term tests, samples were cured for approximately one month prior to testing.

Table 3.6

SUMMARY OF PERMEABILITY RESULTS

Mix Design	Permeability (cm/sec)	(ft/day)	180-Day Permeability (cm/sec)	(ft/day)
A-2-0L	9.2E-08	2.6E-04		
A-2-10L	5.2E-07	1.5E-03	5.8E-06	1.6E-02
A-2-10L*	4.7E-06	1.3E-02		
A-2-20L	6.9E-07	1.9E-03	1.2E-06	3.4E-03
A-2-20L*	2.0E-06	5.7E-03		
A-2-10LG	6.3E-07	1.8E-03		
A-2-15C	1.2E-06	3.4E-03		
A-2-15C*	1.7E-05	4.8E-02		
A-8-0L	5.0E-08	1.4E-04		
A-8-10L	-----	-----	1.4E-07	4.0E-04
A-8-20L	1.4E-06	4.0E-03		
A-8-10LG	5.0E-07	1.4E-03		
A-8-15C	3.5E-07	9.9E-04		
C-2-0L	6.0E-08	1.7E-04		
C-2-10L	1.6E-07	4.5E-04	3.7E-07	1.0E-03
C-2-20L	1.9E-07	5.4E-04		
C-2-10LG*	6.1E-05	1.7E-01		
C-2-15C*	3.1E-06	8.8E-03		
C-8-0L	5.1E-08	1.4E-04		
C-8-10L	6.4E-07	1.8E-03		
C-8-10L*	3.3E-05	9.3E-02		
C-8-20L	9.4E-08	2.7E-04		
C-8-10LG	1.7E-07	4.8E-04		

* Denotes test run by falling head permeability method to the low permeability of the clays.

Permeability of untreated clays averaged 1.8 x 10^{-4} ft/day (6.3 x 10^{-8} cm/sec). The average permeability of all treated clays was 1.5 x 10^{-3} ft/day (5.2 x 10^{-7} cm/sec), an increase of 8 times. These averages do not include results of falling head tests, due to problems with that apparatus which caused inaccurate results. The range of permeability increase was from 1.8 (for mix C-8-20L) to over 350 (for mix A-8-20L) times the permeability of untreated clay.

Four permeability samples were allowed to cure for more than one-half of a year. In each case, permeability increased with longer curing time, on the order of 2 to 10 times the 28-day permeability. The overall increase in the permeability with time is of benefit to lime columns, as it allows them to dissipate excess pore water pressure faster than surrounding clays, thereby acting as vertical drains.

3.7 LEACHING AND COMPACTION

A series of tests was performed to investigate the effect of leaching on the strength of the clay. Samples were prepared as usual in 3-inch diameter PVC pipe, except that a cotton wick was placed along the center axis of the compacted mixes. Water was allowed to leach through the sample along the wick for a period of 1 month. However, less than one pore volume ofwater was leached through most of the samples due to the low permeability of the clays.

After 1 month, samples were cut lengthwise along the same axis as the wick, and tested for strength by the fall cone method. Fall cone strength tests were run at the outer edge, the middle, and next to the wick. No significant loss of strength was detected near the wick.

The compaction, or moisture-density relationship, was investigated on Clay B mixed with 10 percent lime to investigate the possibility of using clay/lime mixtures as fill material for standard construction efforts. Due to the sensitive nature of the hydration of the lime, the following time constraints were used to prepare samples:

o Sample moisture mixing	15 ± 0 minutes
o Compaction into Standard Proctor mold	10 ± 2 minutes
o Extruding sample and taking moisture content	5 ± 1 minutes
Total time of test	30 minutes

The optimum moisture content was 57 percent while the maximum dry density of the amended clay was 67.8 pcf. The optimum moisture content is higher than for most soils used as fill material, but is far lower than the typical moisture content of clay from even an old clay disposal area. Considerable drying would therefore be needed before the clay could be used as a fill. Further, the maximum dry density of the material is considerably lower than for typical fill material. Therefore, a mix of phosphatic clay and lime is not considered to be practical for use as a fill material.

Section 4

PRACTICAL IMPLICATIONS AND RECOMMENDATIONS

4.1 DESIGN PROTOCOL

Results of this study indicate that changes in engineering characteristics of phosphatic clay amended with lime, lime and gypsum and cement are favorable. Specifically, plasticity was significantly reduced; strength of amended samples was increased from 20 to 200 times or more than initial clay strength; deformation was reduced to one-tenth or less; and permeability was increased an average of one order of magnitude.

In order for the above results to be used for engineering design in the manufacture of lime columns, however, appropriate field conditions must be met. Lime columns may be a practical, economically attractive foundation treatment when either the water table has been lowered or a sufficient surcharge has been placed to increase the solids content of the clay.

Design Example

A "typica1" design example is actually impossible, because there are no “typical” deposits of waste clay. The geometry of the mine cuts in which the clay is deposited can be extremely variable. However, for example purposes, the following initial conditions of a clay deposit are given:

LL (Liquid limit)	= 185 (liquid limit)
PL (Plastic limit)	= 55 (plastic limit)
PI (Plasticity Index)	= 130 (LL - PL)
Depth of deposit	= 28.0 feet
Depth to water table	= 5.0 feet
Average solids content	= 40%
Average void ratio	= 4.0
Average Permeability	= 1.4×10^{-4} ft/day (5×10^{-8} cm/s)
Average Compression Index	= 1.76

The Atterberg Limits of the clay are in the normal range for phosphatic waste clay in Central Florida. Other parameters were derived from correlations or calculated using a proprietary computer program named ULTPHOS, developed at Bromwell & Carrier, Inc. to compute the conditions of a waste clay pond which has been allowed to consolidate for several years. The depth of the water table was set to 5 feet in the program to allow sufficient consolidation such that conditions are right for lime columns. The variation of density, void ratio, solids content and permeability with depth is shown in Figure 4.1. These conditions represent the conditions of a clay pond prior to loading without lime columns.

If a 50- x 30-foot surcharge with a stress equal to 500 psf is applied to untreated clay with the above conditions, the clay will consolidate about 1.6 feet, or about 7 percent, at the center of the surcharge. Settlement at the corners would be 0.6 feet. These values of settlement were calculated using a proprietary computer program named PHOSCON, also developed at Bromwell & Carrier, Inc. Settlement was also hand-checked using a one-dimensional approximation, and very close agreement was found with a settlement of 2.0 feet.

When lime columns are installed, the settlements will be reduced. In order to model the settlements with lime columns, it is first necessary to select a clay, then the lime content and the appropriate compression index. In terms of solids Content, the clay which best matches the "typical" clay is Clay A-8, with an initial solids content of 41 percent, which corresponds to a moisture content of 143 percent. As an initial trial, 10 percent lime mix is selected for the columns.

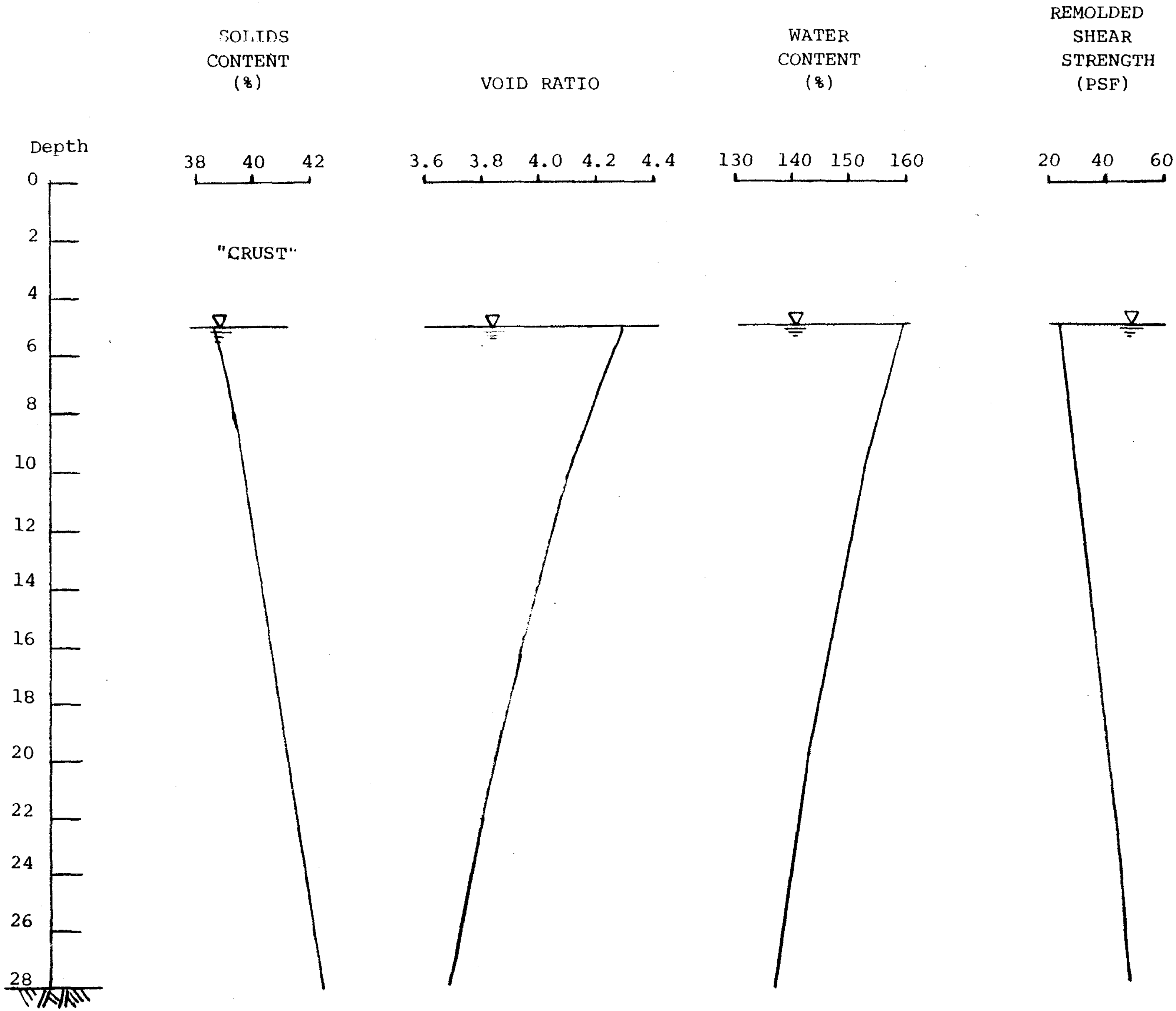

Figure 4.1 Initial conditions of clay deposit for design example.

From Table 3.5 of this report, A-8-10L has a Recompression Index of 0.024. The Recompression Index (C_r), which is the flat slope of the void ratio vs. log stress curve for cemented soils, should be used to calculate the settlement ofthe columns. This C_r corresponds to a Constrained Modulus of 298,450, based on the following relationship:

$$M = \frac{(1 + e_o)\ \sigma_{va}}{0.435\ C_c}$$

where σ_{va} = average vertical stress

e_o = initial void ratio

Broms (1984) uses the following equation to calculate total settlements (σh) of a structure supported on lime columns:

$$\Delta h = \frac{qH}{a\ M_{col} + (1 - a)\ M_{soil}}$$

where q = applied surcharge stress

H = thickness of compressible deposit

M = constrained modulus of the soil

a = ratio of column area to total loaded area

It is assumed in the above equation that the load is distributed to both the columns and the clay. In this case the applied stress is 500 psf and the thickness of compressible clay deposit is 23 feet (the compressibility of the 5-foot thick crust is neglected). It is further assumed that the columns will cover 10 percent of the area and that they are mixed to the bottom of the clay deposit.

The maximum settlement calculated with lime columns (using the above equation) was 2.9 inches, for an overall reduction in settlement of approximately 88 percent. For many cases, this settlement maybe tolerable if the majority of the settlements occur during construction instead of after construction. Other methods to reduce settlement include either decreasing the spacing of the columns or building a surcharge embankment to complete the consolidation prior to grading to final construction elevations.

4.2 BUILDING CODES

The locally accepted building code is the Southern Building Code Congress International (SBCCI) Standard Building Code (1986). While lime columns are not specifically mentioned as an approved foundation treatment for buildings, provision is given in Section 1303.2 for the use of special types of piles. The Code states that other types of piles may be used, "subject to the approval of the Building Official, upon submission of acceptable test data, calculations, and other information relating to the structural properties and load capacity of such piles". Allowable stresses on the piles may not exceed the limitations set forth in the Code.

4.3 RECOMMENDATIONS

Results of this laboratory investigation strongly indicate that the lime column method can be used as a foundation treatment for phosphatic waste clay deposits with an average solids content at or near 40 percent. Field conditions of a potential site can be altered by ditching and desiccating, preloading, draining, or otherwise imparting sufficient stress to achieve this solids content. Then, lime columns can be used in conjunction with other stabilization methods to achieve a soil bearing capacity sufficient to support one-story buildings.

Therefore, it is recommended that further research be conducted in this area to adequately define the technical and economic feasibility of the lime column method. Specifically, it is recommended to proceed with a field demonstration of lime columns. A comparison of strength, consolidation, and permeability measurements on lime columns manufactured in the field and laboratory with prepared lime/clay mixes is needed to correlate the results of this study to actual field conditions. Additionally, measurement of actual total and differential settlements can be compared to predicted settlements.

It is further recommended that a series of centrifuge simulations of lime columns be conducted, whereby the effect of various loading, column spacing, and other conditions can be investigated at a substantially reduced cost compared with field measurements.

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ULTPHOS, (c) Copyright Bromwell & Carrier, Inc., 1986.

APPENDIX

LITERATURE REVIEW

A major objective of this study is to review the available literature references pertaining to: the uses of lime for stabilization of soils (including roadwork); research efforts regarding stabilization of phosphatic clay; and, on the lime column method of stabilization.

STABILIZATION WITH LIME

Lime has been used for centuries for the stabilization of clays. For example, lime was used along with alabaster (gypsum) for mortar and plaster to build the huge limestone pyramids of ancient Egypt (Boynton, 1980). The Romans used lime in their remarkable civil engineering achievements and apparently learned about lime from the Greeks. Since around 1900, progressively larger quantities of lime have been used in industry as a chemical reagent. Currently, more than 90 percent of the total amount of lime produced is sold as a chemical in its oxide and hydroxide form. Lime is the principal, lowest-cost alkali available and is produced in greater quantity than any other chemical with the exception of sulfuric acid (National Lime Association, 1981). In 1983, 14.9 million tons of lime was produced in the U.S. (U.S. Bureau of Mines, 1983).

Recent figures show that approximately 17% of the lime produced in the United States is used for construction purposes, with the rest used for agriculture and chemical/industrial purposes. The percentage for construction is growing as new applications for lime are discovered. Lime stabilization methods for road and soil stabilization are widely used to permanently consolidate soils and base materials. This results in a marked increase in soil strength and bearing capacity and a decrease in water sensitivity and volume change during wet/dry cycles. Many states, including Alabama, have written standard procedures for lime stabilization of roads (Alabama State Department of Transportation, 1984).

Lime is produced in primarily two forms: unslaked, CaO, and slaked lime, $Ca(OH)_2$. Unslaked lime results from the calcination or or burning of limestone, and to a lesser extent, shell material. In the United States, two classes of unslaked lime are available: high calcium lime, containing less than 5% magnesium oxide (MgO), and dolomitic quicklime, containing 35% to 40% MgO. Unslaked lime is available in the following standard sizes:

1) Lump lime: particle sizes about 2 to 8 inches in diameter

2) Crushed lime: the most common form, 1/4 to 2 inches

3) Granular lime: #8 to #80 sieve (2.36 to 0.18 mm)

4) Ground lime: almost all particles pass the #8 sieve, and 40-50% finer than #100 sieve (0.15 mm)

5) Pulverized lime: almost all particles passing #20 sieve (0.83 mm) and 85-95% finer than #100 sieve

6) Pelletized lime: fines pressed into approximately l-inch pellets

Slaked lime is a dry powder obtained by treating unslaked lime with enough water to satisfy its chemical affinity for water under conditions of hydration. Slaked lime may contain 1% water in excess of that needed to complete hydration. Slaked lime is air classified to produce the necessary fineness, with normal grades containing 75% to 95% particles finer than the #200 sieve (0.074 microns). However, gradations as fine as 99.5% finer than the #325 sieve (0.045 microns) are available.

Soil-Lime Mixtures

The properties of soil-lime mixtures depend on: 1) the properties of the soil, 2) the properties of the lime (viz., chemical composition and gradation), 3) lime content, 4) method of mixing, 5) duration of “mellowing” period (time between mixing and placement), 6) curing environment (moisture conditions, chemistry and temperature), and 7) age.

In general, high plasticity (CH) clays are quite reactive, or pozzolanic, with alkaline soils usually more responsive than acidic soils. Sulfate has been reported to have a detrimental effect on lime stabilization due to the formation of the highly expansive mineral ettringite. There are contradictory findings in the literature regarding the role of organics. Townsend and Donaghe (1976) report that soils with more than 1% organic content do not usually respond well to lime treatment. While acknowledging this generality, Sabry and Parcher (1979) report favorable response in a clay with 1.5% organics, and Mitchell and Hooper (1961) found satisfactory performance with an expansive clay having 8% organic content. Arman and Munfakh (1972) also report improved behavior in eight of the 11 organic clays tested, with organic contents as high as 20%.

Regarding lime properties, Remus and Davidson (1961) presented results of three montmorillonitic clay soils treated with various limes at a dosage of 6 percent. The

7- and 28-day cured strengths were significantly higher using dolomitic monohydrate lime than with calcitic slaked lime, at both Standard and Modified Proctor densities. Alexander et al. (1972) studied the stabilizing effect of two hydrated limes and three unslaked limes on three compacted low-plasticity (CL) clays. Unslaked lime was found to be more effective in improving strength. At lime contents above 2%, the coarser unslaked limes were more effective, since the fine limes caused a great deal of flocculation, thereby reducing the density of the soil. The authors noted that when using unslaked lime, the mixture should be loose cured for about one day to prevent expansion caused by the hydration of the lime.

The amount of lime to be added depends on the desired improvement. No established mix design procedures exist for determining optimum lime content for modification, and in fact no good quantitative definition of workability of compactibility are known to exist. Criteria for modification lime content often include requirements such as no further reduction in plasticity index with increasing lime, or an acceptable reduction in the plasticity index for the particular stabilization objective. Typica1 lime contents for modification of CH clays are on the order of 3% to 10% lime (Boynton, 1980).

Mix design procedures for determining optimum stabilization of lime content are much better established. Townsend and Donaghe (1976) and Transportation Research Board (1976a) present eleven such procedures in current use. One of the most commonly employed is presented by Eades and Grim (1966) and consists of adding increasing amounts of lime to a 20% solids content soil slurry. The optimum lime content is taken to be the lowest percentage of lime that produces a slurry pH of 12.4, one hour after mixing . While this procedure ensures sufficient free lime for pozzolanic reaction to occur, it cannot be used to indicate how much stabilization will occur. Other mix design procedures involve experimentally determining the lime content which produces a certain unconfined strength (such as 300 psi) or maximum plastic limit. Other procedures may indirectly predict the optimum stabilization lime content based on index properties of the soil. Typica1 optimum stabilization of lime contents for CH clays are up to 6% using unslaked lime,and 8% using slaked lime.

A reduction in the plasticity of the clay is reported when clay is mixed with lime (Broms and Bowman, 1978). The plasticity is reduced through the physio-chemica1 phenomenon of cation exchange (Roads and Streets, 1979). The addition of lime to reactive soil causes an immediate reduction in plasticity (PI). According to Brandl (1981), the plastic limit always increases, while the liquid limit either remains unchanged or sometimes decreases, depending on the amount and activity of the colloidal clay minerals.

Some conflicting evidence and opinions exist regarding the compaction characteristics of soil-lime mixtures. Townsend and Donaghe (1976) reported that the addition of modification lime contents to clays causes only mi nor changes in the optimum moisture content, wopt, and a decrease in the maximum dry density. Brandl (1981) also reported a reduction in dry density with the addition of lime, but states that in general there is an immediate increase in wopt, thus easing compactability. He notes, however, that if the the mixture remains uncompacted and is able to carbonate, then the optimum water content decreases because the particles coagulate (become weakly cemented by the carbonates).

Mitchell and Hooper (1961) assessed the effectiveness of 4% dolomitic slaked lime for stabilizing an organic (8%) expansive clay (LL=46; PI=25). A 24-hour delay between mixing and compaction had detrimental effects in terms of density (8 pcf lower and strength (30% lower) at a given compactive effort. However, when compactive effort was increased to provide the same density, the strengths were comparable. The authors noted that the increase in uniformity (obtained after re-mixing and prior to compaction) and handling ease produced by delayed compaction or “mellowing" may offset the losses in density and strength, or may justify the additional compactive effort. Neubauer and Thompson (1972) performed tests to determine the increase in workability and compactibility of uncured lime-treated clays, including high plasticity clays. Up to 6% lime was added to the clays at moisture contents above optimum. The authors stated that the effects of cation exchange and flocculation were sufficient to greatly improve adverse soil conditions, particularly for expediting construction and for temporary roads. Sabry and Parcher (1979) noted that lime-treated soils compacted wet of optimum attain superior strength, at short curing periods, probably because of more uniform diffusion of lime and the more homogeneous curing environment.

Lime Used in Construction

Lime is now commonly used as a soil stabilizer in the construction industry, especially road construction. Hydrated lime is more common as it can be readily pumped or injected into the ground. Hydrated lime mixed with flyash has been pressure injected to depths of up to 40 feet as a grout for landfills (Public Works, 1984). Quicklime (CaO) has been used to stabilize canals and roads where swelling clays were involved. The lime acts to reduce swell, increase strength, stability, and wet/dry durability (Roads and Streets, 1975). It is common to use 3 to 4 percent lime for these applications.

STABILIZATION OF PHOSPHATIC CLAY WITH LIME

Very little research has been done on stabilization of phosphatic clay with lime. Other potential stabilizers which have been investigated include phosphogypsum and flyash (Barwood, 1986).

Zellars-Williams, Inc. (1983) performed laboratory strength tests on mixes of slaked lime and phosphatic clay at initial clay solids contents less than or equal to 42 percent, and also investigated the effect of lime on flocculation of dilute clays. The majority of the vane shear strength readings were 0, although strengths as high as 0.23 tsf were recorded. Strength was also measured by penetrometer and viscometer. The authors concluded that the effectiveness of lime addition to phosphatic clays was dependent on the amount of water present in the system, and that treatment of massive volumes of fresh waste clays was not economical, even for clays pretreated to obtain high clay solids contents. Selfridge (1985) investigated the consolidation and curing strength behavior of phosphatic clay mixed with lime and with gypsum. Clays from several different Central Florida mines were tested at initial clay solids contents ranging from 12 to 14 percent with 4, 8, and 12 percent lime added. 28-day strengths up to 25 psf were obtained, with strengths as much as 9 times the initial strength of the untreated clay. The immediate strength of the treated clay was nearly twice that of the untreated clay in many tests. Strength tests run on clay sample’s with very high gypsum contents (1:1 to 12:1 gypsum to clay ratios) also exhibited strength gain. Selfridge found a significant decrease in the time rate of consolidation in the clays, as well as a decrease in the overall amount of consolidation. These results were attributed to flocculation and agglomeration of the clay/lime particles which made them behave more like sand and less like clay. An in-house study was conducted by the Florida Institute of Phosphate Research on strength of phosphatic clay mixed with various quantities of lime, phosphogypsum, and other accelerators (Barwood, 1986). Phosphatic waste clay samples from seven plants were prepared at clay solids content of 5, 10, 20, and 30 percent. Lime was added at 1, 3, 7, 10 and 20 percent by weight. Phosphogypsum was added to other samples at 5, 15, 35, 50, and 100 percent by weight. Some mixes of lime and gypsum were also prepared at a 1:5 lime to gypsum ratio. Temperatures up to 90 degrees Celsius were used on some samples to accelerate the curing process. Unfortunately, the maximum penetration resistance. which could be measured was only 400 psf, which corresponds to a shear strength of 70 psf.

The tests performed by FIPR indicate that there was little to no strength gain for any mixes with clay at 5 or 10 percent solids content. Moderate to high strength gains were observed on clays at 20 percent solids with a minimum of 7 percent lime with 35 percent phosphogypsum. Samples with 10 percent lime showed variable strength gains depending on the mine from which the clay was sampled. Interestingly, samples which were mixed with phosphogypsum only, even up to 50 percent, showed no strength gain. Another series of tests was performed on samples with "excess" lime (20 percent) and with phosphogypsum which were cured at high temperatures. Very high strengths were obtained with these mixes and, in some instances, no penetration could be observed with the laboratory equipment. Accelerated temperatures, however, did not produce any strength gain for samples with phosphogypsum only. Finally, samples with clays at 30 percent solids exhibited similar trends to those at 20 percent solids, but had higher strengths.

THE LIME COLUMN METHOD

The lime column method, where unslaked lime or quicklime (CaO) is mixed in-situ with very soft clay, is used extensively in Sweden, Finland, and Norway to stabilize roads and excavations and as foundation for light structures (Broms, 1984). A mixing tool shaped as a large dough mixer with 0.5 m (20.0 inches) diameter is used to mix in-situ the lime with the clay. The maximum length of the columns is 15 m (50 feet) with presently available machines. The powdered lime is forced down the Kelly of the lime column machine to the mixing tool using compressed air.

A specially designed track-mounted carrier or a standard front wheel loader can be used for the installation of the columns. The lime is stored in a 2.5 m container pulled by the rig or the loader. About 50 lime columns can be manufactured in 8 to 10 hours under favorable conditions. The cost of lime columns in Sweden is about 40 Sw C_r per meter (US $1.07/ft.) which makes the method very competitive compared with steel or precast concrete piles or soil improvement methods (preloading, stone columns, embankment piles, etc.).

In Scandinavia, a specially designed track-mounted carrier (Linden-Alimac LPS 4) or a standard front wheel loader (e.g. Volvo M LM 641) is used for the installation of the lime columns. The LPS 4 machine can be used in weak soil conditions due to the low contact pressure (about 625 psf). The minimum required shear strength to carry the machine is about 125 psf. Since a 2 to 3-foot thick fill may be required for initial surface treatment, the heavier front wheel loader can be used. The capacity (columns/day) of a front wheel loader may be a little lower than a track-mounted carrier. However, the difference should not be large.

The LPS 4 has a strip chart recorder where the amount of lime injected into each column is plotted as a function of the depth. A permanent record is thus obtained for each column.

The lime column method is mainly used to stabilize very soft inorganic clays with a liquid limit less than 100 percent, an organic content less than 3 percent, and an undrained shear strength which is less than about 20 kPa (400 psf). The method has also been used successfully in soft organic clay with a liquid limit of up to 180 percent. Gypsum was used in addition to the lime under those circumstances.

The response of the clay with lime has been found to vary depending on the properties of the clay. The shear strength generally increases with increasing solids content and with decreasing plasticity index. Clay mineralogy is also important.

Stabilization With Lime (CaO or $Ca(OH)_2$)

The shear strength of soft clay can be increased with either hydrated lime ($Ca(OH)_2$) or with quicklime (CaO). Quicklime has been found to be much more effective than hydrated lime because of the reduction in water content that takes place during the hydration of the quicklime (Broms, 1984). Only a small reduction of the water content may be required to increase the shear strength significantly due to the reduction of the plasticity index by the lime. Addition of lime significantly increases the plastic limit while the liquid limit is hardly affected, thereby reducing the plasticity index of the clay.

Clays which are calcium-saturated or which have a high initial plasticity index tend to reduce the effectiveness of the lime. When the main mineral component is montmorillonite, the lime column method appears to work well (Broms, 1986).

The optimum lime content with respect to the dry weight of the soil has been found to range from 6 to 10 per cent for most clays with a water content less than about 100 percent. The relative increase of the undrained shear strength generally decreases with increasing lime content. The increase of the shear strength above 12 percent lime is generally small. In addition, the maximum amount of quicklime that can be added may be limited by the boiling of the pore water because of the heat released during the slaking of the lime.

Stabilization With Lime (CaO) and Gypsum ($CaSO_4$)

Lime-gypsum mixes have been employed in the manufacture of lime columns (Broms, 1986). Gypsum has been found to be especially effective in soils with a high initial water content and with high liquid and plastic limits as is the case for organic soils. Gypsum appears to speed up the chemical reactions so that a relatively high shear strength can be obtained within one to three months.

Gypsum forms needle-like particles (ettringite) with the clay which binds the soil together. Experience has shown that the optimum effect for lime column strength is generally obtained with about one-third gypsum and two-thirds lime. However, there are several disadvantages with gypsum. Because of the crystalline water in the gypsum, the unslaked lime has a tendency to draw water from the gypsum causing caking or balling of the lime when stored for several days prior to field placement. In practice, the gypsum should be mixed with the lime at the site a few hours before it is used. The gypsum must also be dried and ground, which increases the overall cost. Contamination of the ground water by the gypsum should also be considered, as well as the use of sulfate resistant cement for adjacent concrete structures.

The fluidity of the finely-ground lime and gypsum must be sufficient to easily inject into the soil using compressed air. The same requirements with respect to grain size distribution of lime-gypsum mixes should be satisfied as for cement. Otherwise, plugging of the lime column injection equipment is possible.

Stabilization With Cement

Stabilization with cement has been found to be successful even for relatively high plasticity clays. Cement is used extensively in Japan to stabilize relatively soft clays with a high plasticity index. The effectiveness generally increases with increasing soil solids content and with decreasing plasticity index. The shear strength that can be obtained increases with increasing cement content. The relative increase in strength, however, decreases with the increasing percentage of cement.

More cement than lime is normally required to obtain a given shear strength (Broms, 1986). The ultimate strength is generally obtained earlier with cement than with lime and a higher shear strength can often be obtained when the cement content is high (20% to 30%).

A more thorough mixing is required when cement is used compared with lime in order to obtain the required shear strength. Cement often reduces the permeability of the columns. The permeability also decreases with curing time. This reduction can be particularly large in the first week after the mixing.

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